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POWER TRANSFER BETWEEN TWO ANTENNAS WITH SPECIAL REFERENCE TO POLARIZATION

Beuhring W. Pike

Air Force Systems Command
Vandenberg Air Force Base, California

December 1965

AFWTR-TR-65-1

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BEUHRING W. PIKE, P.E.
RANGE SYSTEMS ENGINEERING

TECHNICAL REPORT NO. AFWTR-TR-65-1

DECEMBER 1965

AIR FORCE WESTERN TEST RANGE
AIR FORCE SYSTEMS COMMAND
VANDENBERG AIR FORCE BASE, CALIFORNIA 93437

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by

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FOREWORD

Radio is not the only means of transmitting information to or from a vehicle such as a spacecraft, but it is by far the most important. In many instances (particularly with rocket propelled vehicles) the information to be transmitted via the radio link is, in terms of time and money, of great value; in some cases, where human life will be at risk, the information to be transmitted is of a value beyond price.

For these reasons one desires to be able to analyze a hypothetical radio link and calculate the power that would be delivered to a radio receiver by the receiver's antenna. In order to make such calculations one needs to calculate first the free-space case and to then apply corrections to account for the effects of the medium and its boundaries.

The literature abounds with guides for calculating the free-space power transfer between two antennas having matched polarizations. However, literature covering the cases wherein the two antennas are not of matched polarizations is scarce. For this reason, the following paper has been developed to provide the necessary equations in complete and convenient form. This paper provides also methods of applying antenna radiation pattern representations to the solution of the equations.

A subsidiary purpose of this paper is to point out the overwhelming importance of polarization by showing that every receiving antenna is completely "blind" to some radio wave because the polarization mismatch loss is infinitely large. It is hoped that the proof given herein will result in greater application of means of avoiding polarization mismatch losses — means such as Polarization Diversity Reception (PDR) and Polarization Alternation of Transmissions (PAT).

This paper was begun in 1961 and nearly completed while the author was employed by the U. S. Navy as the Instrumentation Consultant of the Range Development Department of the Pacific Missile Range (Pt. Mugu, California) prior to his position being transferred to Air Force Western Test Range, Vandenberg Air Force Base, California in January, 1965.[*1]

This paper, which evolved through more than thirteen draft versions, benefited from efforts of many people:

*1. The technical content of this paper reached essentially its present form by August 1964; copies of that draft were given to several people, including members of the Electronic Trajectory Measurements Working Group of the Inter-Range Instrumentation Group.

FOREWORD (Cont'd)

1. The writer is indebted to the late MR. ROBERT F. BENTON (formerly Senior Technical Consultant of the Range Development Department of the Pacific Missile Range) for making available the time for the early phases of the development of this paper, for encouragement, and for assistance on the mathematics involved in the development of the equations for the polarization mismatch loss where linearly polarized waves and/or antennas are involved.

2. Very early in the development of this paper, assistance was given the author by DR. A. V. DONNELLY, (then PMR Staff Consultant; now teaching at Arizona State University), by MR. LLOYD RITLAND (PMR Instrumentation Systems Division), and by MR. DWIGHT L. McKEE (now of the PMR Electronics Development Division).

3. MR. GEORGE W. MORRIS, JR. (now of the Range Instrumentation Performance Evaluation Branch of the PMR Range Operations Department) assisted the author many times on the mathematical development (and made some of the calculations).

4. MR. EUGENE M. FETNER (of the Air Force Eastern Test Range, Patrick Air Force Base, Florida) made major contributions to the development of Appendix D (see reference 29, Acknowledgements)

5. The penultimate PMR manuscript draft of this paper was reviewed for technical accuracy (at the request of the author) by an ad hoc committee established by DR. G. W. BRAUN, PMR Chief Scientist.

PMR Review Committee:

MR. WILLIAM A. BOWEN, JR., Technical Consultant, Chief Scientist's Office (Code 01-3).

MR. JERALD LEISH, Head, Command Guidance Branch (Code N322).

MR. GEORGE W. MORRIS, JR., Mathematician, Range Instrumentation Evaluation Branch (Code 3274).

MR. CULLEN B. TENDICK, Head, Radio Branch (Code 3161).

6. The author's final PMR typescript was reviewed by MR. M. M. MATSEN, Deputy PMR Range Development Officer, and by MR. K. I. LICHTI, Head, PMR Range Analysis and Planning Division (then Acting Deputy Range Development Officer), who both raised some mathematical questions and made suggestions that were incorporated to improve the clarity of the mathematical developments and the ease of access to the definitions of symbols and terms.

BEUHRING W. PIKE, P. E.
(Calif. E-3994, Tex. E-5916).
B.S. in E.E., the Rice University, 1942.
Senior Member, IEEE.
Member, RESA. Member ETMWG of IRIG.
(4184 Arcturus Ave.,
Lompoc, Calif., 93436)

FOREWORD (Cont'd)

APPROVAL

This technical report has been reviewed and edited by the Scientific and Technical Information Office, Air Force Western Test Range, Vandenberg Air Force Base, California, 93437.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Stanley R. Radom
STANLEY R. RADOM
Technical Director
AF Western Test Range

LESLIE K. SKEWS
Major, USAF
Chief, Range Technical Services Branch
AF Western Test Range

ABSTRACT

The literature abounds with examples of a convenient equation ("the beacon equation") for calculating the free-space power transfer between two widely spaced radio antennas having polarizations that are matched for maximum power transfer. On the other hand, convenient equations for making such calculations where the polarizations are not matched are very scarce. In this paper the well known beacon equation has been combined with a published (but relatively little known) general equation for polarization mismatch loss, so as to yield a complete general equation for calculating the power transfer between two widely spaced antennas in free-space. For convenience, the portion of the general power transfer equation that accounts for polarization mismatch loss has been reduced to yield a special equation for each of the five limiting cases. Also given are discussions of polarization problems and solutions in radio and radar, and a discussion of antenna radiation field representation methods and their use in calculating the power transfer between two antennas. This 75 page Technical Report includes a Glossary of 125 terms and a Bibliography of 68 references.

DESCRIPTORS FOR COORDINATE INDEXING

(The principal descriptors are underlined)

<u>Aircraft</u>	Patterns
<u>Antennas</u>	<u>Polarization</u>
Bibliography	<u>Power Gain</u>
Coupling	<u>Power Transfer</u>
<u>Equations</u>	Propagation
IEEE Standard	Radar
IRE Standard	Radiation
<u>IRIG Standard</u>	<u>Radio</u>
Magneto-Ionic	<u>Spacecraft</u>

NOTE: These descriptors are not identical to similar descriptors used by Defense Documentation Center (DDC)

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INTRODUCTION

Readily found in the literature is an equation (sometimes called The Beacon Equation) for calculating the power transfer between two antennas of matched polarizations when the antennas are in free-space and in the far-field (the Fraunhofer Region) of one another. However, literature covering all the cases in which the polarizations are not matched is relatively very scarce.[*2]

Most aircraft antennas and spacecraft antennas are rigidly fixed to the vehicle's body, and are required to have extremely broad angular coverage in order to provide simultaneous coupling with many other antennas at separate remote locations (and/or to permit large angular movements of the vehicle). Because of this, nearly every vehicle antenna unavoidably has a free-space radiation field whose power gain function and polarization functions are extremely complex. For purposes of free-space power transfer calculations involving an antenna of this kind, one must obtain, from the power gain functions, the Power Gain of each of the two antennas in the direction of the other. Also, one must calculate, from the polarization functions, the Polarization Mismatch Loss between the radio wave and the receiving antenna.[*3]

This paper gives, in ready-reference form, a well known equation for calculating the free-space power transfer between two antennas when one knows the Frequency, the Distance between the antennas, the Power Gain of each of the antennas in the direction of the other, the Polarization Mismatch Loss between the radio wave and the receiving antenna, and any miscellaneous system losses (or gains).

In addition, this paper gives a published but relatively little known general equation for calculating the free-space Polarization Mismatch Loss when one knows A. the Ellipticity Ratio (including the "sense") of each of the two antennas, and B. the Polarization Mismatch Angle between the polarization ellipses of the two antennas.

For convenience, this Polarization Mismatch Loss equation is given also in five reduced forms covering the five special cases where one (or both) of the antennas is of a polarization that is a limiting case of elliptical polarization - that is - circularly polarized, or linearly polarized. Although some of these reduced equations are well known, others are not. Since their derivation may not be obvious, the development of the five equations is given in Appendix C.

---

*2. The reader is invited to observe that most of the writers who give an equation for power transfer between two antennas in free-space not only do not include a factor to account for polarization mismatch loss but also do not warn the reader that the equation is invalid for other than matched polarizations. Among those writers who do include a factor for the polarization mismatch loss, very few give an equation for calculating the value of the polarization mismatch loss factor.

*3. Because of the overwhelming importance of polarization in the transfer of power between two antennas, a general discussion, "Polarization Problems in Radio and Radar" is given as the first appendix of this paper.

Appendix C also contains a proof of the highly significant fact that under far-field or Fraunhofer Region conditions every receiving antenna is completely "blind" to some radio wave because the Polarization Mismatch Loss is infinitely large.

This proof is given to emphasize the importance of Polarization Diversity Reception (PDR), wherein two orthogonally polarized receiving antennas each feed one of two independent receivers whose outputs are combined (or utilized independently) and of Polarization Alternation of Transmissions (PAT), wherein alternate pulses (or pulse groups) have orthogonal polarizations.

The Power Transfer Equation given is for two antennas in free-space. For antennas not in free-space, the equation can be used by including system losses and gains not already included (among these are those caused by multipath wave-interference, normal refraction, anomalous propagation, absorption by the medium, dispersion by the medium, scattering by objects, and diffraction over the horizon). The Polarization Mismatch Loss equations can be used for antennas not in free-space by taking into account any in-transit change of the wave polarization, such as is caused by reflection and by magneto-ionic propagation.

It is the author's hope that this paper will help to bridge the hiatus that exists today between theory and its application. Because of the critical importance of the subject of this paper, the author requests immediate notification of any errors that may be found herein.

This paper contains 125 symbols and terms, 17 of which have been coined herein, and all of which are defined in Appendix E. Of the 68 references listed in the "References and Bibliography" section, 32 are cited herein.

Throughout this paper each personal name (and the name of each organization issuing an anonymous publication) is indicated thusly: A.U. THOR

NOTE: This page is intentionally blank so that Equation 1 will face Equations 2 through 7.

1. THE POWER TRANSFER EQUATION:

A general equation for the power transfer between two widely separated antennas in free-space is given below in ready-reference form and is developed and discussed in Appendix B.

$$P_{R(dbW)} = P_{T(dbW)} + \left[G_{T(dbI)} + G_{R(dbI)} + \Sigma G_{(db)}\right] - \left[X_{(db)} + \Sigma A_{(db)}\right] - \left[20 \log_{10} D_{(L)} + K + 20 \log_{10} F_{(Mc/S)}\right] \quad (1)$$

Where:

P_R = Power available at output port of receiving antenna (in ± db with respect to reference power W, ordinarily one watt).

P_T = Power into input port of transmitting antenna (in ± db with respect to reference power W).

G_T = Transmitting antenna's power gain in direction of receiving antenna (in ± db relative to isotropic antenna having no loss).

G_R = Receiving antenna's power gain in direction of transmitting antenna (in ± db relative to isotropic antenna having no loss).

ΣG = Sum of any additional power gains (in+ db).

X = Polarization mismatch loss (in+db). (See equations on next page)

ΣA = Sum of any additional power attenuations (in+db).

D = Distance between the two antennas (in L units).

K = Constant depending on L, the unit of length selected; where ▲ (picus) is a decimal point:

L	K	L	K
Foot, International . .	−37▲87	Kilometer	+ 32▲45
Yard, International . .	−28▲33	Mile, Statute . .	+ 36▲58
Meter	−27▲55	Naut. Mi., Int. .	+ 37▲82

F = Frequency, in Megacycles per Second, or in Mega Hertz (MHz).

QUALIFYING NOTES FOR THE POWER TRANSFER EQUATION:

a. In Equation 1, it is assumed that there is only one signal source and no noise sources.

b. Equation 1 is valid only when each of the two antennas is in the far-field or Fraunhofer Region of the other, here defined as beginning at a distance of $2d^2/\lambda$ and extending infinitely, where d is the largest projected linear dimension of the antenna aperture and where λ is the wavelength (references 26, 56 and 64).

c. For antennas in other than a non-bounded vacuum, Equation 1 would be slightly in error in that the values given for K were calculated for the vacuum velocity of propagation, V (reference 65). For most real cases, this error is extremely small and can be ignored.

d. For antennas in other than a non-bounded vacuum, one must allow for the effects of the medium and its boundaries. See Appendixes A through E.

e. For definitions of symbols and terms, see Appendix E.

1a. POLARIZATION MISMATCH LOSS (X).

Equations for calculating the Polarization Mismatch Loss between two widely separated antennas in free-space are given below in ready-reference form and are developed and discussed in Appendix C.

Case: (Polarizations)	X = Polarization Mismatch Loss (in+db) =	
Ellip. $\longleftrightarrow$ Ellip.	$-10\log_{10}\left\{\frac{1}{2}+\frac{1}{2}\left[\frac{4r_T r_R+(1-r_T^2)(1-r_R^2)\ (\mathrm{Cos}\ 2\beta)}{(1+r_T^2)\ (1+r_R^2)}\right]\right\}$	(2)
Ellip. $\longleftrightarrow$ Lin.	$-10\log_{10}\left\{\frac{1}{2}-\frac{1}{2}\left[\frac{(1-r_E^2)\qquad(\mathrm{Cos}\ 2\beta)}{(1+r_E^2)}\right]\right\}$	(3)
Ellip. $\longleftrightarrow$ Circ.	$-10\log_{10}\left\{\frac{1}{2}+\frac{1}{2}\left[\frac{2r_C r_E}{(1+r_E^2)}\right]\right\}$	(4)
Lin. $\longleftrightarrow$ Lin.	$-10\log_{10}\left\{\frac{1}{2}+\frac{1}{2}\left[\frac{(\mathrm{Cos}\ 2\beta)}{1}\right]\right\}$	(5)
Lin. $\longleftrightarrow$ Circ.	$-10\log_{10}\left\{\frac{1}{2}-\frac{1}{2}\left[\frac{0}{2}\right]\right\} = +3\ \mathrm{db}$	(6)
Circ. $\longleftrightarrow$ Circ.	$-10\log_{10}\left\{\frac{1}{2}+\frac{1}{2}\left[r_{TC}\,r_{RC}\right]\right\}$ $= 0\ \mathrm{db}$ When $r_{TC} = r_{RC}$; $= +\infty\ \mathrm{db}$ When $r_{TC} = -r_{RC}$	(7)

Where*4: r = Ellipticity Ratio, the signed voltage ratio of the major axis of the polarization ellipse to its minor axis, where $(1 \le |r| \le \infty)$. *5

β = Polarization Mismatch Angle, $(0^\circ \le \beta \le 90^\circ)$. *5

T means Transmitting; R means Receiving.

E means Elliptically Polarized; C means Circularly Polarized.

*4: For definitions see Appendix E, Glossary of Symbols and Terms.

*5: See Appendixes A through E.

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APPENDIX A

POLARIZATION PROBLEMS IN RADIO AND RADAR

A1. THEOREM: For every radio antenna that feeds a single receiver (for every receiving antenna having a single output port), there can be incident upon the antenna a radio wave of a polarization orthogonal to that of the receiver's antenna such that the polarization mismatch loss is infinitely large, and the antenna therefore delivers to the receiver none of the energy of the incident wave. On the other hand, when the polarization match is optimum the polarization mismatch loss is zero. This theorem is proved in Appendix C.

A2. RADIATION OF RADIO WAVES BY SPACE VEHICLES AND AIRBORNE VEHICLES. In the general case, a radio wave radiated from a space vehicle or an airborne vehicle is an extremely complicated wave whose intensity and polarization vary greatly as a function of the direction from the vehicle. This is true both for a radio wave scattered by a vehicle as an echoing radar target and for the wave radiated by a fixed antenna on a vehicle.

a. In the general case, any object upon which a radio wave impinges radiates (by scattering) a secondary radio wave whose intensity and polarization both vary greatly as functions of the direction from the object. Any wave energy scattered back to the antenna from which the incident wave came will (in the general case) have a polarization such that a component of the wave is of a polarization orthogonal to that of the antenna that radiated the primary wave. In some instances, this orthogonal component is the only component present in the back-scattered wave.

b. A vehicle's radio transmitting antenna having a radiation field that is fixed with respect to the vehicle radiates a wave whose intensity and polarization both vary greatly as functions of the direction from the vehicle. In the general case, wherever the vehicle's radio wave impinges upon any other antenna, the incident wave has a polarization such that a component of the wave is of a polarization orthogonal to the polarization of the antenna upon which the wave impinges.

A3. RECEPTION OF RADIO WAVES RADIATED FROM VEHICLES.

a. When the antenna upon which a radio wave impinges is intended for extracting energy from the wave and delivering it to a radio receiver, any wave component that is of the same polarization as the polarization of the antenna is accepted, but any wave component that is of a polarization orthogonal to the polarivation of the antenna is totally rejected. That is, the Polarization Mismatch Loss is infinitely great.

b. In the general case, a radio wave coming from a vehicle to a receiving antenna site can, at that site, be of any polarization whatever (and can vary in polarization as the vehicle moves). The ONLY way to insure that none of the energy that is available in the wave incident on the receiving aperture is rejected and lost, through polarization mismatch, is to provide Polarization Diversity Reception (PDR). PDR is accomplished by having two orthogonally polarized receiving antennas, each feeding one of two separate receivers whose outputs are combined (or utilized separately). Note that both of the two orthogonally polarized antennas can be served by the same lens, horn, or parabolic reflector for increasing the power gain of the antenna in one direction (at the expense of another).

A4. RECEPTION BY VEHICLES OF RADIO WAVES.

The principle of reciprocity between antennas indicates that for a vehicle's receiving antenna having characteristics as described in paragraph A2b above, there can be, for every direction from the vehicle, some incident radio wave whose polarization is orthogonal to that of the vehicle's antenna in that direction such that the vehicle's antenna delivers to its receiver none of the energy of the incident wave.

a. This vehicle antenna Polarization Mismatch Loss problem can, in principle, be solved by applying PDR. However, it is very difficult to provide two vehicle antennas having both a broad angular coverage and orthogonal polarizations in every direction covered. In addition, there is the problem of providing a second receiver (and possibly an output combiner).

(1) For pulse systems only, an alternate method that is almost as good as PDR is Polarization Alternation of Transmissions (PAT), wherein the transmitting antenna radiates pulses (or pulse groups) that alternate between two orthogonal

polarizations. Note that when PAT is used, the pulse repetition frequency should be high enough to provide adequate system performance even under the condition where one of the two wave-polarizations happens to be exactly orthogonal to the polarization of the receiving antenna.

(2) For continuous-wave systems, a similar thing can be done by having two orthogonally polarized waves transmitted on slightly different frequencies and by having two combined-output receivers fed from the same antenna. Here it is important that the receiving antenna's characteristics be essentially the same, as regards polarization, at both of the frequencies. This method can be called Polarization Frequency Diversity (PFD).

A5. PULSE RADAR SYSTEMS FOR ECHO TRACKING OF VEHICLES.

a. With conventional echo tracking radars, much of the transmitted wave energy that could be received as echo energy is not captured.

(1) An echoing target, in the general case, scatters back to the radar a wave whose intensity is a function of both the intensity and the polarization of the wave incident upon the target. For an extreme example, a thin short-circuited dipole parallel to the electric field vector of a linearly polarized wave intercepts and scatters much energy; the same dipole when perpendicular to the electric field vector intercepts and scatters essentially no energy. The probability of such an effect causing a long-duration null in the intensity of the wave scattered back from a moving vehicle can be reduced by alternating the polarization of the radar's transmitted pulses (or pulse-groups) between two orthogonal polarizations (say Linear-Horizontal and Linear-"Vertical"). This method, called PAT, has another advantage with racons (radar beacons), as is described below in paragraph A6.

(2) An echoing target, in the general case, not only scatters the incident wave but also transforms the polarization of the wave such that some (or all) of the energy in the return wave at a conventional radar's receiving antenna is of a polarization orthogonal to the polarization of the radar's receiving antenna.*6, *7, *8 The

*6 H. GENT, et al. (reference 19).
*7 G.E. Co. (reference 18).
*8 J.R. COPELAND (reference 11).

orthogonal component is rejected by the radar's receiving antenna. This waste of extremely expensive energy can be avoided by employing PDR as described in paragraph A3b.

(3) A pulse method only slightly less effective than dual-receiver PDR is to have a single receiver whose input is commutated between the outputs of the two orthogonally polarized antennas on an alternating, time-sharing basis. This method can be called Polarization Alternation Reception (PAR).

b. It should be noted that most of the publications that give an equation for "Radar Range" do not take into account the loss caused by a mismatch between the polarization of the receiving antenna and the polarization of the back-scattered wave arriving at that antenna. Consider, for example, the calculation of the tracking range of a single-sense (Left-Handed, or Right-Handed)[*9] circularly polarized radar on an echoing target that is an essentially perfect "polarization mirror" (a large flat plate of metal, a large three-sided corner-reflector of metal or a large metal sphere). In the limit, the wave reflected (scattered) back to the receiving antenna is circularly polarized in the opposite sense so that the Polarization Mismatch Loss is infinitely large and the tracking range is therefore zero. It should be noted also that the "Scattering Cross Section" of an echoing target (needed in the Radar Range Equation for determining the amount of energy scattered back toward the radar's receiving antenna) is (except in the case of a perfect homogeneous sphere) a function of both the direction from the target to the radar <u>and</u> the polarization of the wave incident upon the target. Therefore, wave polarization must be taken into account not only at the receiving antenna, but also at the echoing target.[*10]

c. Although PAT and PDR (or PAR) in an echo-tracking pulse radar each have some advantages, the simultaneous application of PAT with PDR provides the best possible avoidance of polarization losses (and PAT with PAR is nearly as good).

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*9 See, in Appendix E, <u>Sense; of an electromagnetic wave (or an antenna).</u>

*10 For an example of a Radar Range Equation that <u>does</u> include a polarization factor, see DONALD E. KERR (reference 33).

A6. PULSE RADAR SYSTEMS FOR RACON (RADAR BEACON) TRACKING.

a. Unlike a wave scattered by an object in a radar beam, the intensity and polarization of the wave transmitted by a racon have essentially no correlation to the intensity and polarization of the incident wave from the radar. For this reason it is even more desirable to provide PDR (or PAR) in a racon-tracking radar than it is in an echo-tracking radar.

b. Similarly, as discussed in paragraph A4, there is only an imperfect correlation between the polarization of the incident wave from a radar and the polarization of the racon's receiving antenna in the direction of the radar. The resulting Polarization Mismatch Loss can be reduced by applying PDR (or PAR) at the racon. However, the difficulty of doing this with a vehicle racon is such that it will be preferable in most cases to apply PAT (which is nearly as good for this purpose).

c. With a pulse radar/racon system there is another method of solving the racon antenna problem. In this method the space vehicle or airborne vehicle carrying the racon is equipped with a multiplicity of racon antennas having complementary radiation patterns (complementary as to the directions of their intensity nulls and orthogonal as to their polarizations in each direction), each feeding a separate receiver. The outputs of the receivers are used to trigger the racon's reply and, during the delay before the response, to switch the racon's transmitter to the antenna that had delivered the most energy to a receiver. By the principle of reciprocity between receiving and transmitting antennas, that antenna is the most favorable one for transmitting the racon's reply to the interrogating radar. This method can be called Reply Antenna Selection (RAS). For other racon diversity methods, see Paragraph C-2 of reference 30.

d. It should be noted that most of the publications that give "Racon (Beacon) Range" equations do not take into account the loss caused by a mismatch between the polarization of the receiving antenna and the polarization of the wave incident on that antenna.

A7. For general information about racons (radar beacons), see A. ROBERTS, Radar Beacons (reference 50) and IRIG System Standards for C-Band (5 cm) Instrumentation Radars and Beacons (reference 30). For recent books on the analysis of radar and racon systems, see BARTON *11 and SKOLNIK *12. For recent books regarding antenna considerations, see SPANGENBERG *13 and HANSEN *14.

A8. For tracking instrumentation radars with PAT and PDR features (for which radars this author wrote the performance specifications), see Bureau of Naval Weapons contract NOw 64-0620, with Sperry Gyroscope Co., Great Neck, N.Y., for four AN/FPQ-10-(XN-1) radars, to be installed at Pacific Missile Range. The most modern previous range instrumentation radar, the AN/FPQ-6 (and its transportable version AN/TPQ-18) does not incorporate PAT and PDR (or PAR). However, the operator can select either (I), a linear "vertical" polarization mode, or (II), a circular polarization mode in which the radar transmits left-handed circularly polarized (LHCP) waves but receives right-handed circularly polarized (RHCP) waves *15. Mode (II) provides an improvement in echo tracking of some targets. For racon tracking, the mode option enables the radar operator to switch the polar-

*11 DAVID K. BARTON (reference 4). NOTE: After his book was already in galley-proof form, Barton added (on Page 132) a brief reference to this paper, as it was then planned to be published by Pacific Missile Range.

*12 MERRILL I. SKOLNIK (reference 58). See particularly Chapter 7, "Antennas".

*13 KARL R. SPANGENBERG, Editor (reference 59). On page 37, T.H. LEE points out that polarization loss is not included in the radar range equation derived. On pages 65-67, J.L. BELLAMY discusses polarization mismatch losses in the racon range equation given, but does not give an equation for calculating those losses. Note, on page 21, that the definition of "sense" given by A.S. DUNBAR is the definition used by most physicists and is opposite to that given by IRE (now IEEE). See "Sense" in Appendix E hereto.

*14 R.C. HANSEN (reference 20). Volume I of II was sighted but Volume II was not available.

*15 The AN/FPQ-6 (AN/TPQ-18) instruction manual does not make clear which definition of "sense" is intended. M.R. PAGLEE, of the Radio Corporation of America, advised the author that the one used in the IRE (IEEE) definition.

ization so as to avoid the infinite polarization mismatch loss that occurs when the beacon's antenna (wave) polarization becomes either (A), for Mode (I), linear-horizontal, or (B), for Mode (II), circular (either LHCP or RHCP). Although this polarization flexibility is very useful to a highly skilled operator, the combination of PAT with PDR (or PAR) is much more effective because it is completely automatic and, in some instances, can produce smaller polarization mismatch losses.

A9. WARNING: Sometimes a tracking radar not having PDR (or PAR) will track with a side lobe of the antenna and refuse to track with the main lobe, thereby introducing a large (and usually unsuspected) angle error. Such a condition can occur when the polarization of the return wave becomes exactly orthogonal to that of the main lobe, but the polarization of a side lobe is at least slightly different from that of the main lobe (which is almost always the case). See SAMUEL SILVER (reference 56), page 423, regarding cross-polarization in side lobes; see R.C. HANSEN, (reference 20), pages 144 and 152, and A. ROBERTS (reference 50), page 57.

A10. CAUTION: Ordinarily, the angle measuring accuracy of a high-accuracy tracking radar such as the AN/FPQ-6 (AN/TPQ-18) is a function of the polarization of the wave being received such that polarizations other than optimum (usual in racon tracking) can produce angle errors that are many times the rated inaccuracy of the radar. This problem can be solved by incorporating PDR in the radar. The radar then receives predominately the polarization giving the better signal-to-noise ratio and therefore automatically discriminates against the cross-polarized component that causes the gross angle errors.

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APPENDIX B

DEVELOPMENT OF POWER TRANSFER EQUATION

In a nonbounded vacuum, the fraction of the radio frequency power fed into the input port of a transmitting antenna that is available from the output port of a receiving antenna having its polarization matched to that of the radio wave (and located at a distance sufficiently great that each antenna is within the far-field or Fraunhofer Region of the other) can be determined from the beacon (racon) equation derived by H.H. BAILEY in Radar Beacons (reference 50)*16. This equation, with the ratio of velocity to frequency (V/f) substituted for wavelength (λ), is

$$\psi_2 = \psi_1 \left[\frac{(V/4\pi)^2 \gamma_1 \ \gamma_2}{f^2 D^2} \right] \tag{B1}$$

where*17

ψ_2 = Power available from receiving antenna's output port*18

ψ_1 = Power fed into transmitting antenna's input port*18

V = Velocity of the radio wave (of light) in a nonbounded vacuum. The Union Radioscientifique Internationale (URSI) value is: 299,792.5 ± 0.4 km/sec. (reference 65)

π = 3.14159 · · ·

γ_1 = Power gain factor*18 of transmitting antenna in direction of receiving antenna, with respect to that of an isotropic radiator with no loss

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*16 For a fundamental derivation of this equation, see also BERNARD M. OLIVER (reference 44). (NOTE: Neither Dr. Bailey nor Dr. Oliver give an equation for calculating the power transfer for cases in which the polarizations are not matched.)

*17 See Appendix E for definitions of the symbols and terms used in this paper.

*18 Note: The port at which the power gain is measured must be defined and only that port must be referred to in subsequent calculations. Note that the power gain factor is not expressed in decibels.

γ_2 = Power gain factor[*18] of receiving antenna in direction of transmitting antenna, with respect to that of an isotropic radiator with no loss

f = Frequency of wave in cycles per unit time (t)

D = Distance between the two antennas (reference 42)

This equation can be reduced to equation 1 by expressing it first in log form (all logarithms in this paper are to the base 10):

$$10 \log \psi_2 = 10 \log \psi_1 + \Big[20 \log (V/4\pi) + 10 \log \gamma_1 + 10 \log \gamma_2 - 20 \log f - 20 \log D \Big] \quad \text{(B2)}$$

Then by expressing it in the nomenclature of this paper[*17] and in decibel form, with the reference power (ordinarily 1 watt) indicated by the subscript W, and with the reference for antenna power gain (power gain of an isotropic radiator with no loss) indicated by the subscript I, one obtains:

$$P_{R(dbW)} = P_{T(dbW)} + \left[20 \log\left(\frac{V}{4\pi}\right) + G_{T(dbI)} + G_{R(dbI)} - 20 \log f_{(cycles/t)} - 20 \log D \right] \quad \text{(B3)}$$

If frequency is expressed in megacycles per second (F):

$$P_R = P_T + G_T + G_R + 20 \log \left(\frac{V}{4\pi}\right) - 20 \log F_{(Mc/S)} - 20 \log 10^6 - 20 \log D$$

$$P_R = P_T + G_T + G_R + 20 \log \left(\frac{V}{4\pi}\right) - \left[20 \log F_{(Mc/S)} + 120 + 20 \log D \right] \quad \text{(B4)}$$

Therefore, where the constant $K = 120 - 20 \log (V/4\pi)$:

$$P_{R(dbW)} = P_{T(dbW)} + \left[G_{T(dbI)} + G_{R(dbI)} \right] - \left[20 \log D + K + 20 \log F_{(Mc/S)} \right] \quad \text{(B5)}$$

Inserting terms for the polarization mismatch loss (X), additional power attenuations (A), and any additional power gains (G) into equation B5 gives:

$$P_{R(dbW)} = P_{T(dbW)} + \left[G_{T(dbI)} + G_{R(dbI)} + \Sigma G_{(db)}\right] - \left[X_{(db)} + \Sigma A_{(db)}\right] - \left[20 \log_{10} D + K + 20 \log_{10} F_{(Mc/S)}\right] \quad \text{(B6)}$$

Which is equation 1, the power transfer equation for two antennas each in the far-field (Fraunhofer Region[*19]) of the other.[*20,*21,*22,*23]

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*19 For a discussion of field regions, see SAMUEL SILVER (reference 56) and U.S. AIR FORCE, Handbook of Radio Frequency Radiation Hazards (reference 64). The U.S. NAVY, BUREAU of NAVAL WEAPONS, has a similar (but confidential) radio frequency hazards manual. Also see the forthcoming revised version of reference 26.

*20 Many authors do not mention Polarization Mismatch Loss (X). The writer suspects that one of the assumptions stated by SAMUEL SILVER on page 3 of Reference (56) has been forgotten--Dr. Silver said, regarding the antenna as a receiving device: "In specifying the performance of an antenna, we shall suppose that the polarization of the wave and the impedance characteristics of the detector are such that maximum power is absorbed".

*21 See page 3 of L. THOUREL (reference 62).

*22 See pages 436 and 438 of F.E. TERMAN and J.M. PETTIT (reference 61).

*23 A convenient relation pointed out on page 33-3 of reference 32 is that the power attenuation between two lossless isotropic antennas of matched polarizations, one wavelength apart in free-space, would be 22 db (and that for every doubling of the separation, the attenuation is increased by 6 db).

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APPENDIX C

DEVELOPMENT OF POLARIZATION MISMATCH LOSS EQUATIONS

Significance of Polarization Mismatch

The polarization of an antenna in a given direction from the antenna is defined as the polarization of the far-field (Fraunhofer Region) wave that would be radiated in that direction by the antenna in free-space. The importance of matching the polarization of a receiving antenna to the polarization of the radio wave to be received is shown by the following theorem (which is proved in this appendix).

THEOREM: For every radio antenna that feeds a single receiver (for every receiving antenna that has a single output port), there can be incident upon the antenna a radio wave of a polarization orthogonal[*24] to that of the receiver's antenna such that the polarization mismatch loss is infinitely large, and the antenna therefore delivers to the receiver none of the energy of the incident wave. On the other hand, when the polarization match is optimum, the polarization mismatch loss is zero.

Calculation of Polarization Mismatch Loss (PML)

The polarization mismatch loss can be calculated from one of equations 2 through 7. For the general case, as expressed by equation 2, the following values are needed:

1. Ellipticity ratio[*25] (which includes the sense) of the wave radiated by the transmitting antenna, here called r_T, where $\left[(1 \leq |r_T| \leq \infty)\right]$.

*24 In this paper, "orthogonal" means not only "at 90°" but also means, for elliptical polarizations and for circular polarizations, "of opposite senses and of the same degree of ellipticity" (i.e. $r_R = -r_T$ and, if determinate, $\beta = 90°$).

*25 See Appendix D for methods of determining, and Appendix E for definitions of the symbols and terms used in this paper.

2. Ellipticity ratio*25 (which includes the sense) of the wave that would be radiated by the receiving antenna if it were used for transmitting, here called Γ_R, where $\left[(1 \leq |\Gamma_R| \leq \infty)\right]$.

3. Polarization mismatch angle*25 between the major axes of the polarization ellipses of the two waves, here called β, $(0^\circ \leq \beta \leq 90^\circ)$.

Less data are needed for special cases, where either (or both) of the antennas is linearly polarized or circularly polarized (limiting cases of elliptical polarization), as indicated by equations 3 through 7.

Development of Polarization Mismatch Loss Equation 2

The subject of the reception of elliptically polarized waves with elliptically polarized antennas has been treated by several writers. See W. Sichak and S. Milazzo (reference 55), Leonard Hatkin (reference 22), and V. H. Rumsey et al (reference 51). Dr. Hatkin has presented the following equation (in which "ψ" has been substituted for Hatkin's "P"):

$$\frac{\psi_{Rec.}}{\psi_{Opt.}} = \left[\frac{1}{2} \pm \frac{2r_1 r_2}{(1+r_1^2)\ (1+r_2^2)} + \frac{(1-r_1^2)\ (1-r_2^2)\ \ \cos 2\alpha}{2(1+r_1^2)\ (1+r_2^2)}\right] \quad \text{(C1)}$$

Where $\psi_{Rec.}$ is the power available from a lossless receiving antenna of arbitrary power gain and polarization, where $\psi_{Opt.}$ is the power available from a lossless receiving antenna of the same power gain but whose polarization is matched to the polarization of the incident radio wave, where r is the absolute value of the "axial ratio", and where the minus sign is used when the "senses" are opposite.

Replacing r_1 and r_2 with Γ_T and Γ_R (where $\left[(1 \leq |\Gamma| \leq \infty)\right]$ such that the "sense" of the wave is indicated by the sign of Γ), substituting β for Hatkin's α (in order to agree with reference 29) and rearranging gives:

$$\frac{\psi_{Rec.}}{\psi_{Opt.}} = \left\{\frac{1}{2} + \frac{1}{2}\left[\frac{4\Gamma_T \Gamma_R + (1-\Gamma_T^2)\ (1-\Gamma_R^2)\ (\text{Cos}\ 2\ \beta)}{(1+\Gamma_T^2)\ (1+\Gamma_R^2)}\right]\right\} \quad \text{(C2)}$$

Expressing equation C2 in decibel form, where $X = -10 \log_{10}(\psi_{Rec.}/\psi_{Opt.})$, gives:

$$X(db) = -10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{4 \Gamma_T \Gamma_R + (1-\Gamma_T^2)\ (1-\Gamma_R^2) \quad \text{Cos } 2\beta}{(1+\Gamma_T^2)\ (1+\Gamma_R^2)} \right] \right\}$$

Which is equation 2.[*26]

Reduction of Polarization Mismatch Loss Equation 2 for Special Cases

(NOTE: Case numbers correspond to equation numbers 3 through 7, and are not in numerical sequence)

Case No. 4

When one antenna is elliptically polarized ($\Gamma = \Gamma_E$) and the other is circularly polarized ($\Gamma = \Gamma_C = \pm 1$, depending on the sense), equation 2 becomes:

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{4 \Gamma_C \Gamma_E + (1-\Gamma_C^2)\ (1-\Gamma_E^2)\ (\text{Cos } 2\beta)}{(1+\Gamma_C^2)\ (1+\Gamma_E^2)} \right] \right\}$$

Since $\left| \frac{(1-\Gamma_E^2)}{(1+\Gamma_E^2)} \right| \leq 1$, and $\left| (\text{Cos } 2\beta) \right| \leq 1$;

substituting $(\Gamma_C^2) = (\pm 1)^2$ and simplifying gives:

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{2 \Gamma_C \Gamma_E}{(1+\Gamma_E^2)} \right] \right\} \tag{C3}$$

Which is equation 4.

Case No. 3

When one antenna is elliptically polarized ($\Gamma = \Gamma_E$) and the other is linearly polarized ($\Gamma \rightarrow \infty$), equation 2 can be reduced by dividing both the numerator and the denominator of the term within brackets by Γ_T^2 or Γ_R^2, depending on which

*26 See LEONARD HATKIN in "Erratum for References" (Page 58).

antenna is linearly polarized, and then by taking the limit of X as Γ of the linearly polarized antenna (Γ_L) becomes infinite. Assuming that $\Gamma_E = \Gamma_R$ and dividing by Γ_T^2 gives:

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{4\frac{\Gamma_R}{\Gamma_T} + \left(\frac{1}{\Gamma_T^2} - 1\right)\left(1 - \Gamma_R^2\right) \quad (\text{Cos } 2\beta)}{\left(\frac{1}{\Gamma_T^2} + 1\right) \quad (1 + \Gamma_R^2)} \right] \right\}$$

$$\lim_{\Gamma_T \to \infty} X = -10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{0 + (0-1)\,(1 - \Gamma_R^2) \quad (\text{Cos } 2\beta)}{(0+1) \quad (1 + \Gamma_R^2)} \right] \right\}$$

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} - \frac{1}{2} \left[\frac{(1 - \Gamma_R^2) \quad (\text{Cos } 2\beta)}{(1 + \Gamma_R^2)} \right] \right\} \qquad \text{(C4)}$$

Substituting Γ_E for Γ_R gives:

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} - \frac{1}{2} \left[\frac{(1 - \Gamma_E^2) \quad (\text{Cos } 2\beta)}{(1 + \Gamma_E^2)} \right] \right\}$$

Which is equation 3.

Case No. 5

When both antennas are linearly polarized, dividing the numerator and denominator of the term within brackets in equation C4 by Γ_R^2 and then taking the limit of X as Γ_R becomes infinite gives:

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} - \frac{1}{2} \left[\frac{\left(\frac{1}{\Gamma_R^2} - 1\right) \quad \left(\text{Cos } 2\beta\right)}{\left(\frac{1}{\Gamma_R^2} + 1\right)} \right] \right\}$$

$$\lim_{\Gamma_R \to \infty} X = -10 \log_{10} \left\{ \frac{1}{2} - \frac{1}{2} \left[\frac{(0-1) \quad (\text{Cos } 2\beta)}{(0+1)} \right] \right\}$$

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{\text{Cos } 2\beta}{1} \right] \right\} \qquad \text{(C5)}$$

Which is equation 5. Since $(\frac{1}{2} + \frac{1}{2}\text{Cos } 2\beta) = \text{Cos}^2\beta$, it can be written as:

$$X_{(db)} = -10 \log_{10} \text{Cos}^2 \beta \tag{C5A}$$

or as:

$$X_{(db)} = -20 \log_{10} \text{Cos } \beta \tag{C5B}$$

Case No. 6

When one of the two antennas is linearly polarized and the other is circularly polarized ($\Gamma = \pm 1$), replacing Γ_E by -1 or $+1$ in equation 3, which is

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} - \frac{1}{2} \left[\frac{(1-\Gamma_E^2)\ (\text{Cos } 2\beta)}{(1+\Gamma_E^2)} \right] \right\}$$

Gives

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} \right\} = +3\text{db} \tag{C6}$$

Which is equation 6.

Case No. 7

When both antennas are circularly polarized ($\Gamma_T = \Gamma_{TC} = \pm 1$, and $\Gamma_R = \Gamma_{RC} = \pm 1$) equation 2 becomes:

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{4\Gamma_{TC}\Gamma_{RC} + (1-\Gamma_{TC}^2)\ (1-\Gamma_{RC}^2)\ (\text{Cos } 2\beta)}{(1+\Gamma_{TC}^2)\ (1+\Gamma_{RC}^2)} \right] \right\}$$

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{4\Gamma_{TC}\Gamma_{RC} + 0}{4} \right] \right\}$$

$$X_{(db)} = -10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\Gamma_{TC}\ \Gamma_{RC} \right] \right\} \tag{C7}$$

Which is equation 7.

When $\Gamma_{TC} = \Gamma_{RC}$ it reduces to:

$$X_{(db)} = -10 \log_{10} \left\{ \tfrac{1}{2} + \tfrac{1}{2} \quad \left[1 \right] \right\} \quad = \quad 0 \text{db} \qquad \text{(C7A)}$$

When $\Gamma_{TC} = -\Gamma_{RC}$ it reduces to:

$$X_{(db)} = -10 \log_{10} \left\{ \tfrac{1}{2} + \tfrac{1}{2} \quad \left[-1 \right] \right\} \quad = \quad \infty \text{ db} \qquad \text{(C7B)}$$

Proof of Optimum Polarization Match Theorem

When the two antennas have equal ellipticity ratios $(\Gamma_T = \Gamma_R)$ and the polarization mismatch angle (β) is 0^o, equation 2, which is:

$$X_{(db)} = -10 \log_{10} \left\{ \tfrac{1}{2} + \tfrac{1}{2} \quad \left[\frac{4\Gamma_T \Gamma_R + (1-\Gamma_T^2)\ (1-\Gamma_R^2)\ (\text{Cos } 2\beta)}{(1+\Gamma_T^2)\ (1+\Gamma_R^2)} \right] \right\}$$

reduces to

$$X_{(db)} = -10 \log_{10} \left\{ \tfrac{1}{2} + \tfrac{1}{2} \quad \left[\frac{4\Gamma^2 + (1-2\Gamma^2 + \Gamma^4)\ (1)}{(1 + 2\Gamma^2 + \Gamma^4)} \right] \right\}$$

$$\therefore X_{(db)} = -10 \log_{10} \left\{ \tfrac{1}{2} + \tfrac{1}{2} \quad \left[1 \right] \right\} \quad = 0 \text{db}$$

Which is the value of the polarization mismatch loss when the two polarizations are perfectly matched. This is true also for the special case of two antennas circularly polarized (β is indeterminate). For proof of this special case, see the development of equation C7A, where both antennas are circularly polarized, and are of the same sense. Note that it is only in special cases that identical polarizations are matched polarizations.

Proof of Infinite Polarization Mismatch Loss Theorem

When the two antennas have ellipticity ratios (Γ) that are equal in magnitude but opposite in sign (of opposite sense) and the polarization mismatch angle (β) is 90^o, equation 2, which is:

$$X_{(db)} = -10 \log_{10}\left\{ \tfrac{1}{2} + \tfrac{1}{2} \left[\frac{4\,\Gamma_T\,\Gamma_R + (1-\Gamma_T^2)\,(1-\Gamma_R^2)\,(\text{Cos } 2\beta)}{(1+\Gamma_T^2)\,(1+\Gamma_R^2)} \right] \right\}$$

reduces to

$$X_{(db)} = -10 \log_{10}\left\{ \tfrac{1}{2} + \tfrac{1}{2} \left[\frac{-4\Gamma^2 + (1-\Gamma^2)\,(1-\Gamma^2)\,(-1)}{(1+\Gamma^2)\,(1+\Gamma^2)} \right] \right\}$$

Simplifying gives:

$$X_{(db)} = -10 \log_{10}\left\{ \tfrac{1}{2} - \tfrac{1}{2} \left[1 \right] \right\} = -10 \log_{10}\left\{ 0 \right\}$$

$$\therefore X_{(db)} = -(-\infty) = +\infty \text{ (db)}$$

Note that this is true also for the special case of two antennas circularly polarized (β is indeterminate). For proof of this special case, see the development of equation C7B, where both antennas are circularly polarized, and are of opposite sense.

Therefore, for any receiving antenna having a single output port, there can be incident upon that antenna a radio wave (and therefore there can be a transmitting antenna) of a polarization such that the receiver's antenna cannot deliver to the receiver any of the energy that is in the wave incident upon the receiver's antenna.

In the general case (wherein the radio wave may have any polarization whatever), unless two orthogonally polarized receiving antenna elements are in the receiving aperture with each element feeding a separate receiver, some (or all) of the power that is available in the wave incident upon the receiving aperture will not be captured. It is possible for the captured power to be infinitely smaller than the available power that is lost through the "leakage" that results from a polarization mismatch.

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APPENDIX D

ANTENNA PATTERNS AND THEIR USE IN DETERMINING VALUES NEEDED TO SOLVE THE POWER TRANSFER EQUATION

Antenna Radiation Pattern Coordinate Systems

The complete description of a Fraunhofer Region (far-field) radiation field of an antenna in free-space requires the use of a multidimensional coordinate system, first, to describe the power gain of the antenna in each direction, and second, to describe the polarization of the wave radiated in each direction.

IRE Coordinate System

THE INSTITUTE OF RADIO ENGINEERS (IRE) (now THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE) established a spherical coordinate system for defining directions from an antenna (reference 26). This spherical coordinate system defines an azimuthal angle Φ (0° to 360° "eastward") and a polar angle θ (0° at the "north" pole). This coordinate system is illustrated by Fig. 34-14, on page 34-13, of Antenna Engineering Handbook by HENRY JASIK (reference 32) and on page 444 of Antennas by JOHN D. KRAUS (reference 38)[*27]. Fixed antennas on the surface of the earth usually have $\theta = 0^\circ$ at the zenith and $\Phi = 0^\circ$ at true north.

IRIG Coordinate System

For moving antennas, IRIG (INTER-RANGE INSTRUMENTATION GROUP)[*28] adopted the IRE coordinate system, with θ extended to 180° ("north" to "south"), and established an arbitrary relationship between the spherical coordinate system and body coordinates of a vehicle carrying the antenna (reference 29). The body coordinate system

*27 See JOHN D. KRAUS in Erratum for References (in the References and Bibliography section).

*28 For information about IRIG, see BEUHRING W. PIKE (reference 45), and/or write to Secretariat, Range Commanders Council, White Sands Missile Range, New Mexico.

adopted is the one used by most aerodynamicists. It consists of three orthogonal axes (roll, pitch and yaw) in a right-handed system. The antenna coordinate system and the body coordinate system are related so that the polar axis coincides with the roll axis, with the positive half of the roll axis at $\theta = 0^\circ$, so that the positive half of the pitch axis coincides with $\theta = 90^\circ$ and $\Phi = 90^\circ$, and so that the positive half of the yaw axis coincides with $\theta = 90^\circ$ and $\Phi = 180^\circ$. This IRIG system can be deduced from figure D1. The nomenclature of this paper agrees generally with that of the IRIG standard (reference 29). However, complete agreement was impossible because of the much larger number of symbols required by this paper.

Representation of Measured Data in IRIG Coordinates

Measurements of power gain and polarization of an antenna on a vehicle can be made at a constant distance from the antenna (but in varying directions from the antenna) and plotted on the surface of a sphere (with the antenna-carrying vehicle represented as being at the center of the sphere). For convenience, the spherical surface can be represented on a flat rectangular surface by making a map projection of the spherical surface. The IRIG Standard (reference 29) specifies two projection schemes: an "equal-angle cylindrical projection" and an "equal-area cylindrical projection." Each projection is upon a cylinder with its axis coinciding with the roll axis (the polar axis). Both projection schemes provide a constant value of Φ for a unit of length, on the cylindrical surface, in the Φ direction. The equal-angle scheme provides the same constant value for θ; but the equal-area scheme provides a θ scale such that equal areas anywhere on the sphere are projected as equal areas on the rectangular surface. The equal-angle method is the most commonly used method. The equal-area method has a few special uses, but it is not well suited to matrix charts (described later).

The measured variables can be represented on the rectangular surface by printing a matrix of two-digit whole numbers thereon (reference 10) or by drawing contour lines thereon. The contour type of chart is illustrated by the IRIG Standard

(reference 29)[*29]. Figure D2 illustrates the contour method in the left-hand half of the rectangular surface; the other half illustrates two forms of the matrix method[*30].

A convenient method is to measure the following three variables as functions of the angles θ and Φ, and plot them on three line-contour charts (or matrix charts) according to the IRIG Standard (reference 29) method:

1. Right-handed circularly polarized partial power gain ($\mathfrak{g}_{\widehat{RH}}$)[*31]
2. Left-handed circularly polarized partial power gain ($\mathfrak{g}_{\widehat{LH}}$)[*31]
3. Tilt angle (τ) of the polarization ellipse.[*32]

This method, herein called "ELERT" (for the twirlors $\mathfrak{e}_{\widehat{LH}}$ and $\mathfrak{e}_{\widehat{RH}}$ and for the Tilt Angle τ) is convenient because in the common case where one antenna of a link is a circularly polarized tracking antenna, only a single partial power gain chart for the other antenna is needed (a tilt angle chart is unnecessary). This

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*29 This IRIG Standard was based almost entirely on the pioneering work of the Atlantic Missile Range (now Air Force Eastern Test Range), Patrick Air Force Base, Florida.

*30 The form used for this antenna radiation pattern chart is the author's suggestion for improvements in the presently used National Range Documentation (NRD) form (AFWTR form 104, Sep 64). The principal improvements are the provisions for expanded-scale charts and for plotting either biased matrix charts or biased contour charts. Another major improvement is the elimination of grid lines (which, on the presently used form, often obscure important numbers or signs). In connection with the need for expanded scale charts, many of the presently used antenna charts become unreadable when reproduced because the necessary fine detail is lost in the reproduction process.

*31 According to the IRE (IEEE) (and the IRIG) definition of "sense". For this definition see Appendix E and footnote (*38).

*32 According to the IRIG Standard (reference 29), the tilt angle (τ) is between a tangent line in the θ direction and the major axis of the polarization ellipse. The angle τ is measured counter-clockwise when observing the antenna from outside the sphere, and $0^{\circ} \leq \tau < 180^{\circ}$. See τ on Figure D1 and in Appendix E.

method is desirable in other cases because the direct measurement of the tilt angle is, in most instances, easier than the direct measurement of the otherwise required Relative Phase Angle (δ') between the two orthogonal circularly polarized components of the wave.[*33]

Antenna Radiation Pattern Model

Because of the great complexity of vehicle antenna radiation patterns and of the geometry involved in calculating predictions of the strength of a radio signal, a three-dimensional model illustrating the IRIG coordinate system and the electrical vectors and twirlors involved is an essential aid to understanding. For this reason, the author designed and made a prototype model. The model incorporates a transparent sphere (about 4 inches in diameter) containing a model vehicle (aircraft) surrounded by a transparent cylinder carrying the projected spherical surface and contour chart lines (and matrix chart numerals). Associated with this model are eleven smaller models for illustrating types of antennas, the electric vectors of their radiated fields, and the various cases of polarization mismatch. To see the model prototype (or "Stereo-Realist" type color-slide pictures thereof) direct an inquiry to the attention of the author.

Application of Antenna Radiation Pattern Data

The power transfer equation (equation 1) demands knowledge of the power gain and the Polarization of an antenna in the direction of the other antenna of a radio link. Since direct measurement of the power gain would require the measuring antenna to be of a polarization exactly matched to the polarization of the wave radiated by the antenna being measured, it is more convenient to observe two orthogonal components of the wave. The measured values of the two orthogonal gain components ($\mathfrak{g}$) can be used to calculate the power gain (G). By measuring also the phase relationship of the two orthogonal components of the wave, they can be used in calculating the polarization mismatch loss (X) demanded by equation 1.

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*33 The Relative Phase Angle (δ') is the angle ($0^\circ \leq \delta' < 360^\circ$) between the two counter-rotating field voltage components $\mathfrak{e}_{\widehat{LH}}$ and $\mathfrak{e}_{\widehat{RH}}$ of the field voltage ϵ at the instant $\mathfrak{e}_{\widehat{LH}}$ is in the direction $\tau = 0^\circ$ (the θ direction). δ' is measured in the same direction as τ, therefore $\delta' = 2\tau$. See τ in Figure D1 Note that $\mathfrak{e}_{\widehat{LH}}$ and $\mathfrak{e}_{\widehat{RH}}$ are "Twirlors" (defined in Appendix E and illustrated in Figure D1).

The two orthogonal components can be either circularly polarized components (of opposite "sense") or linearly polarized components, one in the θ direction and one in the Φ direction. The phase relationship between the two linearly polarized orthogonal components can be determined by measuring the electrical phase difference between the components, where the sign of the phase difference indicates the "sense" of the wave.[*34] The phase relationship between two orthogonal components can be determined also by observing both the "sense" of the wave and the tilt angle (τ) of the polarization ellipse of the wave. This is the method used in this paper. In some cases, it is feasible, and easier, to obtain τ indirectly, by measuring, in addition to $\mathfrak{g}_{\widehat{LH}}$ and $\mathfrak{g}_{\widehat{RH}}$, a linearly polarized partial power gain component in the θ direction ($\mathfrak{g}_\theta$) and a linearly polarized partial power gain component in the direction $\tau = 45^\circ$ ($\mathfrak{g}_{45^\circ}$). From these measurements, τ can be computed. However, to provide redundant data for increasing the accuracy, $\mathfrak{g}_\Phi$ and $\mathfrak{g}_{135^\circ}$ can be measured also. For detailed information on this method, see L. CLAYTON AND J. S. HOLLIS (reference 10)[*35]. The forthcoming revised edition of the IRIG Standard (reference 29) will include full information on this method.

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*34 There are in common use two opposite definitions of "sense". See "Sense" and " τ " in the Glossary of Symbols and Terms, Appendix E.

*35 Dr. Clayton kindly supplied the writer with an advance copy of reference (10), in which CLAYTON AND HOLLIS give, as equation (10), an equation that, when expressed in the nomenclature of this paper, is:

$$2\tau = \text{Arc tan}\ \frac{(\mathfrak{e}^2_{45^\circ} - \mathfrak{e}^2_{135^\circ})}{(\mathfrak{e}^2_\theta - \mathfrak{e}^2_\Phi)}$$

They also give a table for determining the quadrant of 2τ according to the signs of the numerator and the denominator of the Tangent of 2τ.

CLAYTON and HOLLIS point out, on page 22, that:

$$\left(\mathfrak{e}^2_{45^\circ} + \mathfrak{e}^2_{135^\circ}\right) = \left(\mathfrak{e}^2_\theta + \mathfrak{e}^2_\Phi\right) = \left(\mathfrak{e}^2_{\widehat{LH}} + \mathfrak{e}^2_{\widehat{RH}}\right)$$

Therefore, one can derive:

$$2\tau = \text{Arc tan}\ \frac{2\mathfrak{e}^2_{45^\circ} - (\mathfrak{e}^2_{\widehat{RH}} + \mathfrak{e}^2_{\widehat{LH}})}{2\mathfrak{e}^2_\theta - (\mathfrak{e}^2_{\widehat{RH}} + \mathfrak{e}^2_{\widehat{LH}})}$$

(continued)

From two sets of ELERT charts, data can be obtained for calculating the antenna power gain and polarization values needed in equation 1 to calculate the power transfer between two antennas in free-space. In the general case, not only are complete power gain and polarization data needed on each of the two antennas, but also complete data on the relative motions, linear and angular, of the two antennas. With complete antenna radiation pattern data and data on the roll, pitch, yaw, and translation of each antenna (as functions of time) the distance (D) and the polarization mismatch angle (β) can be calculated. When the antenna pattern data are in the IRIG form, the aspect angles (θ and Φ) for each of the two antennas can be calculated from the motion data as functions of time. With two sets of θ and Φ

Footnote *35 (continued)

The quadrant ambiguity is resolved by the following data from Table I, on page 8, of CLAYTON AND HOLLIS (reference 10):

$\left[\frac{\text{Sign of the Numerator}}{\text{Sign of the Denominator}}\right]$	2τ
$\left[\frac{+}{+}\right]$	$0^\circ < 2\tau < 90^\circ$
$\left[\frac{+}{-}\right]$	$90^\circ < 2\tau < 180^\circ$
$\left[\frac{-}{-}\right]$	$180^\circ < 2\tau < 270^\circ$
$\left[\frac{-}{+}\right]$	$270^\circ < 2\tau < 360^\circ$
$\left[\frac{0}{+}\right]$	$2\tau = 0^\circ$
$\left[\frac{+}{0}\right]$	$2\tau = 90^\circ$
$\left[\frac{0}{-}\right]$	$2\tau = 180^\circ$
$\left[\frac{-}{0}\right]$	$2\tau = 270^\circ$
$\left[\frac{0}{0}\right]$	τ is indeterminate (circularly polarized wave)

Note: If one wishes to determine τ only, the squared $\mathcal{E}$'s can be relative powers; therefore they can be with respect to any common power reference.

data, the required antenna radiation data can be read from the two sets of antenna charts. A convenient way to do this, for each of the two antennas, is to draw on a transparent overlay sheet, as functions of time, the θ and Φ values that define the line of sight between the two antennas. The θ and Φ values can be plotted as time-labeled points, or as time-labeled uncertainty boxes. The advantage of the overlay sheet method is a single overlay sheet can be used for reading all three charts of a single antenna set, and when a single vehicle antenna is to couple with many other antennas, a single set of vehicle antenna charts can be used with any number of different trajectory aspect overlay charts. Note that a single trajectory aspect overlay chart can be used with antenna charts for all antennas on the same vehicle. The Figure D2 chart has a trajectory aspect line to simulate such a line drawn on a transparent overlay sheet.

The Figure D2 equal-angle chart is one-half contour type and the other half consists of two kinds of the matrix type. For simplicity, this chart has coarser than normal intervals. For charts of the matrix type, alternate (odd) values can be omitted, as shown, thereby displaying (at least roughly) the corresponding contour lines (reference 10). The Figure D2 chart illustrates the use of biased values to eliminate polarity signs from the partial power gain contour labels (or matrix chart values). To obtain the true value, subtract the indicated bias from the contour or matrix value.*36

For overlay-reading, the rectangular area of every chart, including the trajectory aspect overlay chart, must be of the same dimensions to within close tolerances (the Figure D2 chart is not necessarily of the dimensions and the tolerances indicated thereon). When a standard chart is too small to provide the fine detail

*36 WARNING: Some matrix charts have an inverted db scale (and may or may not use a db scale that is also biased. To provide the Figure D2 matrix chart Tilt Angle (τ) range, in "bigrees" (2 degree units), of 00^B thru 89^B requires a printer having 45 keys to provide 90 two-digit characters. The needed 90 characters could be provided with a 44 key machine by deleting 00 and representing it by: a) typing 11 on top of 01 to give 01, and b) deleting 89 and representing it by 11 on top of 10 to give 10. The term "bigree" has been coined from "bi", meaning two, and "gree", from Middle English (from Middle French "gre"), meaning step or degree. For a mnemonic, think of "Big Degree".

required, several expanded-scale standard charts (rather than a larger chart) should be used. Each expanded scale chart should cover either two side-by-side octants of the sphere, or the upper, or lower, half of one octant of the sphere. In these cases the angle scales should have the expanded values.

Note that the coordinate system poles, $\theta = 0^\circ$ and $\theta = 180^\circ$, are useless (except for circularly polarized components) because direction is ambiguous. Therefore, except for circularly polarized components, contour charts, matrix charts and digital tapes cannot correctly include data for θ values of exactly 0° and 180°. One may make measurements at θ values as close to 0° and 180° as desired; ordinarily the closest measurements would be one angle increment (usually 2°, or 1^B) away, and the θ values 0° and 180° would be left blank.

Tilt angle charts have the following noteworthy characteristics:

1. The wave radiated by a theoretical dipole that is in the polar axis (roll axis) is everywhere of zero degrees tilt angle, and the tilt-angle (τ) contour chart is therefore blank.

2. The tilt angle is indeterminate off each end of any dipole (where no energy is radiated).

3. The tilt angle is indeterminate at the poles ($\theta = 0^\circ$ and $\theta = 180^\circ$) for <u>any</u> antenna. If there is a need to resolve this ambiguity, it should be done by measuring the tilt angle ($0^\circ \leq \tau < 180^\circ$) from the pitch plane containing $\Phi = 0^\circ$ (and the roll axis).

4. The tilt angle becomes indeterminate when the wave becomes circularly polarized. If the a matrix value or tilt angle contour to represent this condition is desired, it should be labeled CP (or left blank in the case of a matrix value) to indicate the angle is not determinate.

Because of the vast amount of data required to fully describe a complex radiation field, it is desirable to use automatic means for measuring and plotting antenna patterns. At least two makers of antenna measuring equipment offer instru-

ments for automatic plotting of contour and/or matrix charts having formats similar to the format of the IRIG Standard (reference 29)*37.

Similarly, the magnitude of the calculations involved in solving the power transfer equation (equation 1), particularly when many ground antennas link with a single vehicle antenna, makes it highly desirable to use a high speed electronic digital computer. For this, data must be stored (preferably on magnetic tape) on the ground antenna's location, on the trajectory of the vehicle, and on the radiation patterns of each antenna. Matrix data is well suited to digital tape recording. The Electronic Trajectory Measurements Working Group (ETMWG) of IRIG is developing standard tape formats for such antenna radiation pattern data. These formats will be included in a forthcoming revised edition of reference 29.

The Air Force Eastern Test Range, Patrick Air Force Base, Florida, has developed an IBM 7094 computer program to calculate the vehicle orientation angles, the antenna aspect angles (θ and Φ), and the distance (D), for up to 40 ground-station antennas.

An IBM 7094 computer program to read antenna pattern data and trajectory data (complete vehicle motion data) and then solve the power transfer equation, is being developed at The Air Force Eastern Test Range.

Several of the antenna radiation pattern techniques and standards described herein are directly applicable to the description of other complex multidimensional coherent or quasi-coherent radiation fields (such as the energy scattered by a complex object in a radar or laser beam) and to the description of multidimensional thermal sources of radio frequency noise (such as rocket flames). Similarly, the techniques are useful in describing multidimensional sources of distortion and/or attenuation of radio waves (such as the ion sheath surrounding a space vehicle entering the earth's atmosphere).

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*37 Exercise extreme caution in interpreting antenna radiation pattern charts because there are many different charting methods in use, and some charts are ambiguous.

Calculations From Antenna Radiation Patterns

For the general case, an antenna radiation field description, according to the IRIG Standard method (reference 29), requires at least three charts. Two are required for orthogonal partial components of power gain, and at least one is required to complete a description of the polarization of the wave that would be radiated by the antenna in free-space. Values read from these charts cannot (except in special cases) be used directly in the power transfer equation (equation 1) but can be used to calculate the needed values, as follows.

Power Gain (G)

With the three charts providing $\mathfrak{g}_{\frown{LH}}$, $\mathfrak{g}_{\frown{RH}}$, and τ, the needed power gain (G) can be calculated from:

$$G_{dbI} = 10 \log_{10} \left[\mathrm{alog}_{10}(\mathfrak{g}_{\frown{RH}}/10) + \mathrm{alog}_{10}(\mathfrak{g}_{\frown{LH}}/10) \right] \qquad \text{(D1)}$$

Where the power gain is with respect to an isotropic antenna with no loss and "alog" stands for antilogarithm.

The above equation derives from the fact that the power gain factor (γ) equals the sum of the two orthogonal partial power gain factors ($\gamma_{\frown{RH}}$ and $\gamma_{\frown{LH}}$). Note that the factor γ is not expressed in decibels (but $\mathfrak{g}$ and G are).

Ellipticity Ratio ($\mathfrak{r}$)

In a similar way, the ellipticity ratio ($\mathfrak{r}$)*38 values needed for calculating the polarization mismatch loss (X) can be calculated from the partial power gain charts by means of the following equation:

$$\mathfrak{r} = \left[\frac{\mathrm{alog}_{10}(\mathfrak{g}_{\frown{RH}}/20) + \mathrm{alog}_{10}(\mathfrak{g}_{\frown{LH}}/20)}{\mathrm{alog}_{10}(\mathfrak{g}_{\frown{RH}}/20) - \mathrm{alog}_{10}(\mathfrak{g}_{\frown{LH}}/20)} \right] \qquad \text{(D2)}$$

Where $\mathfrak{r}$ is negative when the wave is $\frown{LH}$ in sense and positive when $\frown{RH}$ in sense.

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*38 By definition (See Appendix E), the ellipticity ratio (which includes the "sense") of the wave, is $\mathfrak{r} = [(\mathfrak{e}_{\frown{RH}} + \mathfrak{e}_{\frown{LH}})/(\mathfrak{e}_{\frown{RH}} - \mathfrak{e}_{\frown{LH}})]$, (the signed voltage ratio of the major axis of the polarization ellipse to its minor axis) where $\mathfrak{e}_{\frown{RH}}$ and $\mathfrak{e}_{\frown{LH}}$ are "Twirlors" and ($1 \le |\mathfrak{r}| \le \infty$). Some writers, including LEONARD HATKIN (reference 22), call this (without the sign) "axial ratio"; others call

(continued)

Polarization Mismatch Angle (β)

Also needed for calculation of the polarization mismatch loss (X) is the polarization mismatch angle (β)[*39]. This can be obtained from the tilt-angle (τ) charts for the two antennas, in conjunction with data on the angular motion of the two antennas. Complete data on the motion of the two antennas will yield the needed distance (D).

Thus, from two sets of antenna radiation pattern charts and from data on the motion of the two antennas, the required information is obtained (when transmitter power and frequency are known) to calculate the power transferred between the two antennas in free-space. When the radio link is not in free-space, additional data must be obtained for insertion in ΣA and ΣG of equation 1 to account for the many additional attenuations (rarely gains) that occur in the propagation of a radio wave through a bounded sensible medium.[*40] Similarly, X must be adjusted for any distortion of the polarization of the wave.[*41]

There are often situations where one, or both of the antennas of a radio link have some characteristics such that not all of the antenna pattern data indicated above are necessary. For example, when an antenna has a well-defined beam that is pointed at the other antenna of the link (a tracking antenna, or one of two fixed

Footnote *38 (continued)

the inverse "axial ratio"; still others call the inverse "ellipticity." The IRE Dictionary of Terms (reference 25) does not include ellipticity ratio but gives axial ratio as "the ratio of the major axis to the minor axis of the polarization ellipse." The ellipticity ratio can be determined by measuring the right-handed and left-handed circularly polarized partial components of power gain (G) in decibels with respect to an isotropic radiator with no loss; i.e., $\mathcal{G}_{\widehat{RH}}$(dbI) and $\mathcal{G}_{\widehat{LH}}$(dbI). When Γ is positive, the wave is right-handed in sense. When Γ is negative, the wave is left-handed in sense. This IRE definition of sense of an electromagnetic wave is opposite to that used in classical physics (see references 25, 26, 27, 28 and 29). By the IRE definition, a "right-handed (clockwise) polarized wave" is "an elliptically polarized transverse electromagnetic wave in which the rotation of the electric field vector is clockwise for an observer looking in the direction of propagation" (references 25 and 28).

*39 The polarization mismatch angle, β, ($0^{\circ} \leq \beta \leq 90^{\circ}$), is the angle between the major axes of the two polarization ellipses. β can be calculated from the relative angular positions of the two antennas and the measured tilt angle (τ) of the polarization ellipse for each antenna.

*40 For example, see WALTER HOLZER (reference 24).

*41 See H. H. KOELLE (reference 37).

antennas of a point-to-point radio link), the power gain (G) of the beam antenna, as seen by the other antenna, is constant. When this beam antenna is circularly polarized, only the circularly polarized partial power gain ($\mathfrak{g}$) chart (of that sense) is needed for each of the two antennas, because the other orthogonal component does not exist in the circularly polarized beam and the tilt angle (τ) is not needed when one of the two antennas is circularly polarized. Similarly, if a tracking antenna is linearly polarized, only one partial power gain, $\mathfrak{g}_{\frown LH}$ or $\mathfrak{g}_{\frown RH}$ (since $\mathfrak{g}_{\frown RH} = \mathfrak{g}_{\frown LH}$) and its tilt angle, τ (which ordinarily is constant), are needed.[*42]

Figure D3 indicates the various possible combinations of antenna types and the radiation pattern data needed for each combination in order to apply the power transfer equation (equation 1).[*43, *44]

*42 Such a radio link is indicated by Figure D3, under Type IIa. An example of such a link is given in reference 30.

*43 For experimental data against which the Polarization Mismatch Loss equation, (equation 2) can be tested, see W. Sichak and S. Milazzo (reference 55).

*44 For a discussion of antennas and noise sources, see P. D. Potter, Chapter 9 of reference 2.

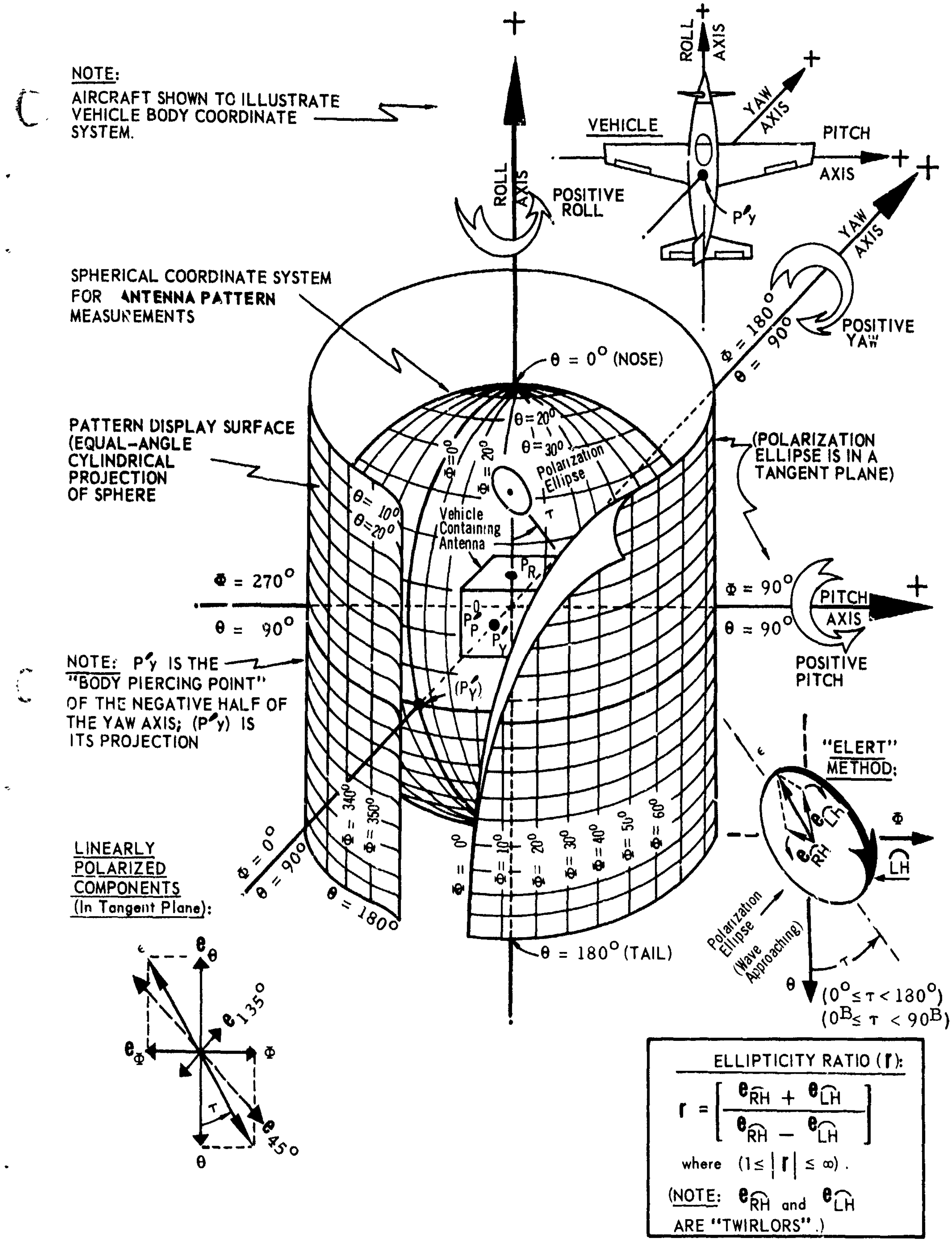

Figure D1. Coordinate Systems

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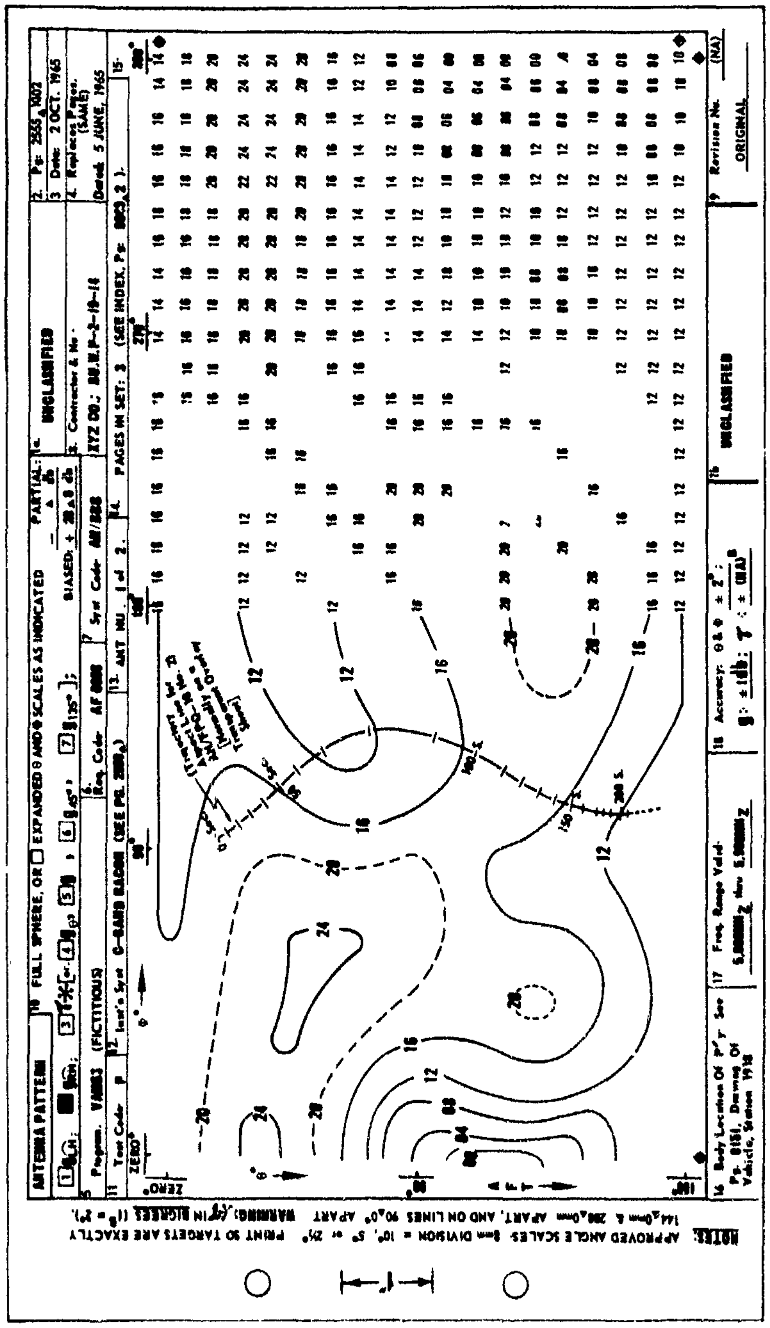

Figure D2A. Contour Chart, Matrix Charts, and Trajectory Aspect Line*45

*45

NOTE: For simplicity, the intervals shown are coarser than usually used. Ordinarily, the contour lines for g would be at 2db intervals. The matrix numbers shown for g are integral multiples of 2 db (00db thru 89db) but the number density (per unit area) in the full matrix ordinarily would be 25 times that shown.

PREPARATION INSTRUCTIONS, ANTENNA RADIATION PATTERN FORM (EQUAL-ANGLE):

I. GENERAL: This form is designed for plotting antenna radiation patterns measured according to IRIG Standard Coordinate System and Data Format for Antenna Patterns, IRIG Document 102-61, Second Printing, April 1963. This form is designed so that it can be used either for Full-Sphere patterns or for Expanded Angle-Scale Patterns, for any of the components that must be plotted, and for either Biased Line-Contour charts or charts consisting of a matrix of biased positive whole numbers, 00 thru 89

II. BLANKS 1 thru 9: Shall be according to National Range Documentation, Page 010, except that the Page Number shall have 8 digits according to the following expansion of the standard National Range Documentation "Point" System: A Page Number shall consist of two Four-Digit numbers separated by a decimal point (▲, a picus):

2 = A System Involving Antennas.	▲	A = Antenna Number (1 thru 5).
K = Kind of System (0 thru 9).		Q = Quadrant (s) of Sphere (0 thru 5).
F = Frequency (0 thru 9).		S = Sexadecimal(1) of Sphere (0 thru 5).
T = Terminal Equip. (0 thru 9).		P = Partial Plotted (0 thru 9).

(For K, F, & T, see NRD 0040 Pages; for Q, S, & P, see Below IV & V:)

III. To Mark a "Ballot Square", fill the square with black ink.

IV. DIRECTIONS COVERED: For a given set of charts(2) use one of the following scales only(3); scanning Left to Right and Top to Bottom:

QS			COVERAGE
00	=	Full-Sphere: ---------	($\Phi = 0^\circ$ to 360°, $\theta = 0^\circ$ to 180°).
10	=	1st Quadrant (4 Sexad.)(1):	($\Phi = 0^\circ$ to 180°, $\theta = 0^\circ$ to 90°).
20	=	2nd " " " "	($\Phi = 180^\circ$ to 360°, $\theta = 0^\circ$ to 90°).
30	=	3rd " " " "	($\Phi = 0^\circ$ to 180°, $\theta = 90^\circ$ to 180°).
40	=	4th " " " "	($\Phi = 180^\circ$ to 360°, $\theta = 90^\circ$ to 180°).
and:			
11	=	1st Quad., 1st Sexad. In:	($\Phi = 0^\circ$ to 90°, $\theta = 0^\circ$ to 45°).
12	=	1st " 2nd " ":	($\Phi = 90^\circ$ to 180°, $\theta = 0^\circ$ to 45°).
13	=	1st " 3rd " ":	($\Phi = 0^\circ$ to 90°, $\theta = 45^\circ$ to 90°).
thru:			
44	=	4th " 4th " ":	($\Phi = 270^\circ$ to 360°, $\theta = 135^\circ$ to 180°).

Note 1: Sexadecimal: One Sixteenth Part of; (Abbrev. Sexad.).

Note 2: All charts of a set have identical numbers except P, (See V).

Note 3. Enter appropriate Φ and θ values in the eight blanks.

V. FUNCTION REPRESENTED BY THIS CHART (Boxes [1] thru [7]):

P

1 = LH Circularly Polarized Partial Gain, g_{LH}, In dbI, Biased.
2 = RH " " " " , g_{RH}, " " "
3 = Tilt Angle, τ, in "Bigrees" ($2^\circ = 1^B$), where ($0^B \leq \tau < 90^B$).
4 = Linearly Polarized Partial Gain in θ Direction, (g_θ), (Biased dbI).
5 = " " " " " Φ " (g_Φ), " "
6 = " " " " " $\tau = 45^\circ$ Direction (g_{45°), (Biased dbI).
7 = " " " " " $\tau = 135^\circ$ " (g_{135°), " "

NOTE: All charts of a set cover the same Direction Angles (QS) but each chart covers a different P above. A set may consist of from one to six charts, depending on the functions required, and on the redundancy desired.

VI. BIASING OF FUNCTION VALUES: Most Matrix Plotters cannot print decimal points and minus signs. Therefore, Matrix Charts and all Contour Charts shall have biased values to eliminate minus signs from gain values. Enter the number of db that must be SUBTRACTED from the Matrix or Contour Value to obtain the true value in dbI.

VII. CHART DIMENSIONS: Since all charts of a given set must be read by a given Trajectory Aspect Overlay Chart, it is essential that all of the charts to be used together have identical dimensions to within close tolerances. Therefore, all charts shall have the stated dimensions. For Line-Contour charts, dimensions are of the grid of non-reproducing lines on which points are plotted; for Matrix Charts, the dimensions are for the centers of the "channels" (between non-reproducing lines) in which matrix numbers are typed. In photographic size-reduction, and in printing, be sure the Φ and θ scales are not distorted beyond stated tolerances. NOTE: if grid lines (or channels) are desired for reading a chart, use a transparent overlay sheet having a grid of such lines or channels.

VIII. ADDITIONAL DATA: When additional antenna data, or trajectory aspect data, must be presented, use a blank antenna pattern form and write (or draw) in the grid area; assign a National Range Documentation Page Number as above but with an additional decimal point and point numbers as needed (or with an entirely different National Range Documentation Page Number).

Figure D2B

LINK TYPE	LINK ANTENNAS[1] ANTENNA "A" Kind	ANTENNA "A" Polarization[2]	ANTENNA "B" Kind	ANTENNA "B" Polarization[2]	LINK TYPE	ANTENNA DATA REQUIRED[3] ANTENNA "A" (Ordinarily on Ground) Measure	ANTENNA "A" To Plot	ANTENNA "A" For Calculating	ANTENNA "B" (Ordinarily on Vehicle) Measure	ANTENNA "B" To Plot	ANTENNA "B" For Calculating
I	Non-Tracking	Elliptical	Non-Tracking	Ellip. ◯	I	$e_{\widehat{LH}}, e_{\widehat{RH}}, \tau$	$g_{\widehat{LH}}, g_{\widehat{RH}}, \tau$	G, r; (β, X)	$e'_{\widehat{LH}}, e'_{\widehat{RH}}, \tau'$	$g'_{\widehat{LH}}, g'_{\widehat{RH}}, \tau'$	G', r'; (β, X)
IIa	Tracking	Linear	Non-Tracking	" "	IIa	$e_{\widehat{LH}}$(or $\widehat{RH}$), τ	$g_{\widehat{LH}}$(or $\widehat{RH}$), τ	G; (β, X)	" " " " "	" " " " "	" " "
IIb	"	Circular	"	" "	IIb	$e_{\widehat{LH}}$ [or $\widehat{RH}$]	$g_{\widehat{LH}}$ [or $\widehat{RH}$]	G $(=g)^{(5)}$; (X)	$e'_{\widehat{LH}}, e'_{\widehat{RH}}$	$g'_{\widehat{LH}}, g'_{\widehat{RH}}$[6]	" "; (X)
IIIa	Tracking	Linear	Tracking	Lin. ／	IIIa	$e_{\widehat{LH}}$(or $\widehat{RH}$), τ	$g_{\widehat{LH}}$(or $\widehat{RH}$), τ	G; (β, X)	$e'_{\widehat{LH}}$(or $\widehat{RH}$), τ'	$g'_{\widehat{LH}}$(or $\widehat{RH}$), τ'	G'; (β, X)
IIIb			"	Circ. ⊙	IIIb	$e_{\widehat{LH}}$(or $\widehat{RH}$)	$g_{\widehat{LH}}$(or $\widehat{RH}$)	G; {X = +3db}	$e'_{\widehat{LH}}$ [or $\widehat{RH}$]	$g'_{\widehat{LH}}$ [or $\widehat{RH}$]	G'; {X=+3db}
IIIc	"	Circular	"	Circ. Same Sense [4]	IIIc	$e_{\widehat{LH}}$ [or $\widehat{RH}$]	$g_{\widehat{LH}}$ [or $\widehat{RH}$]	G; {X= 0db}	" "	" "	G'; {X= 0db}

NOTES (1) Either "A" or "B" may be the transmitting antenna of the two-terminal radio link. Elliptical Polarization includes Linear and Circular polarizations as limiting cases, however, they are treated as separate cases in this paper.

(2) For non-tracking antennas, the Linear and Circular cases have been omitted. This is because the polarization ordinarily is purely linear or circular over a limited aspect angle range such that one must treat all non-tracking antennas as being elliptically polarized (unless they are fixed beam-forming antennas of a point-to-point radio link).

(3) The subscripts $\widehat{LH}$ and $\widehat{RH}$ indicate, respectively, Left-Handed and Right-Handed Circularly Polarized Partial Components, g, of the Power Gain, G, (or Partial Components, e, of the Field voltage, ', where $e_{\widehat{LH}}$ and $e_{\widehat{RH}}$ are "Twirlors"). IN THIS TABLE:

- "$\widehat{LH}$ (or $\widehat{RH}$)" means "Either Sense".
- "$\widehat{LH}$ [or $\widehat{RH}$]" means "Same Sense".

(continued)

- g is a Partial Component of Power Gain (in dbI).
- G is the Power Gain (in dbI) calculated from g data plotted from "ELERT" measurements.
- τ is the Tilt Angle of the Polarization Ellipse $(0^\circ \le \tau < 180^\circ)$, or $(0^B \le \tau < 90^B)$.
- r is the Ellipticity Ratio. $r = \left[\dfrac{e_{\widehat{RH}} + e_{\widehat{LH}}}{e_{\widehat{RH}} - e_{\widehat{LH}}}\right]$; $(1 \le |r| \le \infty)$.
- β is the Polarization Mismatch Angle (calculated from τ data and data on the relative angular positions of the two antennas) $(0^\circ \le \beta \le 90^\circ)$.
- X is the Polarization Mismatch Loss (in + db).

(4) When two antennas have opposite senses, X is infinitely large; therefore, this case is not included in this table.

(5) G is the same as g (of the sense of the Circularly Polarized Antenna).

(6) One is required, and the other is used to evaluate Polarization Diversity Reception (PDR) or Polarization Alternation of Transmissions (PAT).

Figure D3. Types of Radio Link Versus Antenna Data Required

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APPENDIX E

GLOSSARY OF SYMBOLS AND TERMS

(Greek letters are given first, script letters next)

α (alpha): The symbol used by DR. LEONARD HATKIN for Polarization Mismatch Angle, which is called β in this paper.

A (and ΣA): Power attenuation (ΣA is the sum of several power attenuations), expressed in + db.

AFETR: Air Force Eastern Test Range; Headquarters at Patrick AFB, Florida.

AFWTR: Air Force Western Test Range; Headquarters at Vandenberg AFB, California.

Alcedo (▼): A superscript used within a multi-digit number to indicate that digits to the left are significant figures and that digits to the right are insignificant figures written either to establish the location of the decimal point (Picus), or to reduce the errors caused by rounding-off. A term coined herein from the Latin "Alcedo", for "Kingfisher". For a mnemonic, think of "Air Launched Sea Diver."

alog: Antilogarithm. An abbreviation coined in this paper.

AMR: Atlantic Missile Range, (Now AFETR, which see).

β (beta): Polarization Mismatch Angle. The angle between the major axis of the polarization ellipse of a radio wave at a receiving antenna and that of the far-field or Fraunhofer Region radio wave that would be radiated by the receiving antenna if it were used in free-space for transmitting in the reciprocal direction ($0^{\circ} \leq \beta \leq 90^{\circ}$).

Bigree (B): A unit of angle equal to two degrees and indicated by the exponent-like superscript B. A mnemonic term coined in this paper to cover the range $[(0^{\circ} \leq \tau < 180^{\circ}) = (0^{B} \leq \tau < 90^{B})]$ with the highest resolution that is possible without exceeding two numerals. This was necessitated by the limitations of matrix-printing typewriters. For a mnemonic, think of Big Degree.

BUWEPS: United States Navy, Bureau of Naval Weapons.

C: A subscript meaning Circularly Polarized.

CCIR: International Radio Consultative Committee. (See Hz) (See URSI).

CP: An abbreviation for Circularly Polarized.

δ′ (delta prime): A relative phase angle ($0^{\circ} \leq \delta' < 360^{\circ}$). The angle between the two counter-rotating field voltage components $\epsilon_{\widehat{LH}}$ and $\epsilon_{\widehat{RH}}$ ("twirlors") of the field voltage ϵ at the instant that $\epsilon_{\widehat{LH}}$ is in the direction $\tau = 0^{\circ}$ (the θ direction). δ' is measured in the direction of τ, therefore $\delta' = 2\tau$. See Figure D1 and "Twirlor".

D: The distance between two antennas of a radio link, in L units.

d: The largest projected linear dimension of an antenna (or of its beam-forming reflector, lens, or horn). i.e., the largest linear dimension of the aperture.

db (decibel): A unit of the ratio of two power levels; db = $10 \log_{10} \frac{a}{b}$, where a and b are power levels. See dbI and dbW.

dbI: A unit of power gain of an antenna, with respect to that of an isotropic antenna having no loss. The intensity of the far-field wave from an antenna in free-space relative to what it would be if the antenna were replaced by a lossless isotropic antenna. See db.

dbW: A unit of power level with respect to the power level W (one watt unless otherwise specified). See db.

DDC: Defense Documentation Center, Cameron Station, Alexandria, Virginia, 22314.

ϵ (epsilon): Electric field voltage of an electromagnetic wave observed at a fixed point in a plane normal to the direction of propagation of the wave. The resultant of two "twirlors", one of which may be of zero magnitude.

E: A subscript meaning Elliptically Polarized.

$\mathbf{e}$: A partial component of the electric field voltage ϵ .

$\mathbf{e}_{\widehat{LH}}$: The left-handed circularly polarized component of the electric field voltage ϵ, as observed at a fixed point in a plane normal to the direction of propagation. A left-handed "twirlor". See Sense.

$\mathbf{e}_{\widehat{RH}}$: The right-handed circularly polarized component of the electric field voltage ϵ, as observed at a fixed point in a plane normal to the direction of propagation. A right-handed "twirlor". See Sense.

$\mathbf{e}_{\theta}$: The linearly polarized component in the θ direction, of the electric field voltage ϵ .

$\mathbf{e}_{\Phi}$: The linearly polarized component in the Φ direction, of the electric field voltage ϵ .

$\mathbf{e}_{45^o}$: The linearly polarized component in the direction $\tau = 45^o$, of the electric field voltage ϵ .

$\mathbf{e}_{135^o}$: The linearly polarized component in the direction $\tau = 135^o$, of the electric field voltage ϵ .

ELERT: A method of describing the polarization of an electromagnetic wave by defining the left-handed and right-handed circularly polarized partial components $\mathbf{e}_{\widehat{LH}}$ and $\mathbf{e}_{\widehat{RH}}$ (twirlors) of the wave, and the Tilt Angle τ of the polarization ellipse of the wave.

Ellipticity Ratio: See Γ.

ETMWG of IRIG: The Electronic Trajectory Measurements Working Group of the Inter-Range Instrumentation Group. Note: For information, see BEUHRING W. PIKE (reference 45) and/or write to Secretariat, Range Commanders Council, White Sands Missile Range, New Mexico.

F: Frequency, in Megacycles per Second or MegaHertz (one Hertz, Hz, is one cycle per second. See Hz.).

f: Frequency, in cycles per unit time.

Far-field: See Fraunhofer Region.

Foot, International: Exactly one third of one Yard, International (which see).

Fraunhofer Region: That region of an electromagnetic field in which the energy flow from the antenna proceeds essentially as though it were coming from a point source located in the vicinity of the antenna. If the antenna has a well defined aperture (d) in a given aspect, the Fraunhofer Region in that aspect is commonly taken to exist at distances greater than $(2d^2/\lambda)$ from the aperture (λ being the wavelength).

Fresnel Region: The region between the antenna and the Fraunhofer Region.

γ (gamma): Power Gain Factor -- see γ_1 and γ_2.

γ_1: Power Gain Factor of a transmitting antenna in the direction of the receiving antenna, with respect to that of an isotropic antenna. γ is not expressed in dbI.

γ_2: Power Gain Factor of a receiving antenna in the direction of the transmitting antenna, with respect to that of an isotropic antenna. γ is not expressed in dbI.

G (and ΣG): Power Gain (ΣG is the sum of power gains), expressed in + db.

G_R: Power Gain of receiving antenna in the direction of the transmitting antenna, with respect to that of an isotropic antenna, expressed in dbI.

G_T: Power Gain of transmitting antenna in the direction of the receiving antenna, with respect to that of an isotropic antenna, expressed in dbI.

$\mathfrak{g}$: A partial component of the Antenna Power Gain G_R or G_T. See $\mathfrak{g}_{\widehat{LH}}$ and $\mathfrak{g}_{\widehat{RH}}$; $\mathfrak{g}_\theta$ and $\mathfrak{g}_\Phi$; and $\mathfrak{g}_{45^o}$ and $\mathfrak{g}_{135^o}$.

$\mathfrak{g}_{\widehat{LH}}$: The left-handed circularly polarized partial component of the Antenna Power Gain G_R or G_T. One of the orthogonal pair ($\mathfrak{g}_{\widehat{LH}}$ and $\mathfrak{g}_{\widehat{RH}}$).

$\mathfrak{g}_{\widehat{RH}}$: The right-handed circularly polarized partial component of the Antenna Power Gain G_R or G_T. One of the orthogonal pair ($\mathfrak{g}_{\widehat{LH}}$ and $\mathfrak{g}_{\widehat{RH}}$).

$\mathbf{g}_\theta$: The linearly polarized partial component, in the θ direction, of the Antenna Power Gain G_R or G_T. One of the orthogonal pair ($\mathbf{g}_\theta$ and $\mathbf{g}_\Phi$).

$\mathbf{g}_\Phi$: The linearly polarized partial component, in the Φ direction, of the Antenna Power Gain G_R or G_T. One of the orthogonal pair ($\mathbf{g}_\Phi$ and $\mathbf{g}_\theta$).

$\mathbf{g}_{45^o}$: The linearly polarized partial component, in the direction $\tau = 45^o$, of the antenna Power Gain G_R or G_T. One of the orthogonal pair ($\mathbf{g}_{45^o}$ and $\mathbf{g}_{135^o}$).

$\mathbf{g}_{135^o}$: The linearly polarized partial component, in the direction $\tau = 135^o$, of the Antenna Power Gain G_R or G_T. One of the orthogonal pair ($\mathbf{g}_{45^o}$ and $\mathbf{g}_{135^o}$).

Hz (Hertz): One Hertz is one cycle per second. (CCIR Recommendation No. 324, in Documents of the IXth Plenary Assembly, Los Angeles, 1959, Vol. I, page 335; published by International Telecommunication Union, Geneva, 1960.) (reference 31) (see URSI).

∞: Infinity

I: Subscript indicating Isotropic Antenna.

IEEE: The Institute of Electrical and Electronics Engineers. (New York, N.Y.)

Intensity (of an electromagnetic wave): Power radiated per unit solid angle, where the apex of the solid angle is at the source of the wave.

IRE: The Institute of Radio Engineers. Now amalgamated with the American Institute of Electrical Engineers to form the IEEE.

IRIG: The Inter-Range Instrumentation Group, of the Range Commanders Council. For information, see BEUHRING W. PIKE (reference 45) and/or write to Secretariat, Range Commanders Council, White Sands Missile Range, New Mexico.

K: A constant in the Power Transfer Equation whose value is a function of the unit of length selected. See equation 1.

λ (lambda): Wavelength.

L: A selected unit of length. See equation 1. The L in $\overset{\frown}{LH}$ does not mean length.

$\overset{\frown}{LH}$: A subscript meaning left-handed. (See $\overset{\frown}{RH}$ and Sense).

M: Meter, a unit of length.

Nautical Mile International: 1,852* meters. (reference 42)

Orthogonal: In this paper, orthogonal means not only "at 90^o" but also, for elliptical and circular polarizations, "of opposite senses and the same degree of ellipticity." (i.e., $\Gamma_R = -\Gamma_T$ and, if determinate, $\beta = 90^o$).

Φ (phi): Azimuthal angle; one of two angles used to specify a point on the surface of a sphere of observation, the other angle being θ. See Fig. D1.

π (pi): $3_{\blacktriangle}14159\cdots$

ψ (psi): Power.

ψ Opt.: The power available from a lossless radio receiving antenna of Antenna Power Gain G_R when its polarization is perfectly matched to the radio wave. See ψ Rec.

$\psi_{Rec.}$: The power available from a lossless radio receiving antenna of Antenna Power Gain G_R for an arbitrary mismatch between the polarization of the radio wave and the receiving antenna. See $\psi_{Opt.}$

ψ_1: Power fed into transmitting antenna's port.

ψ_2: Power available from port of receiving antenna when the polarization of the antenna is matched to the radio wave.

P_R: Power available at output port of receiving antenna (expressed in $\pm$ dbW).

P_T: Power into input port of transmitting antenna (expressed in $\pm$ dbW).

P_P, and P_P'; (P_P), and (P_P'): P_P is the point where the positive half of the Pitch Axis pierces the outer surface of an antenna-carrying vehicle. P_P' is the corresponding point for the negative half of the Pitch Axis. (P_P) is the projection of P_P onto the surface of the sphere of observation around and centered at the center of gravity of the vehicle, and (P_P') is the corresponding projection of P_P'. See Figure D1.

P_R, and P_R'; (P_R), and (P_R'): Piercing Points of the Roll Axis. See P_P.

P_Y, and P_Y'; (P_Y), and (P_Y'): Piercing Points of the Yaw Axis. See P_P.

PAR: An acronym for Polarization Alternation Reception; coined in this paper.

PAT: An Acronym for Polarization Alternation of Transmissions; coined in this paper.

PDR: An acronym for Polarization Diversity Reception; coined in this paper.

P. E.: Registered Professional Engineer.

Pega ($\blacksquare$): A superscript indicating the entire number is exact by definition. Coined herein from the star Pegasos, of The Great Square of Pegasus: for example $1^{\blacksquare}$ International Yard = $0_{\blacktriangle}9144^{\blacksquare}$ Meter. See V.

PFD: An acronym for Polarization Frequency Diversity; coined in this paper.

Picus (▲): A Decimal Point (see Page 4 and Fig. D2B); coined herein from the Latin "Picus," the "Woodpecker" of Italian and Greek mythology (pronounced p ī k ŭ s). For a mnemonic, remember the woodpecker is a climbing bird; also think of Pi = 3▲14159 • • •

PML: An acronym for Polarization Mismatch Loss; coined in this paper.

PMR: Pacific Missile Range (U. S. Navy); Headquarters at Point Mugu, California.

Port: A place of access to a system where energy may be supplied or withdrawn, or where system variables may be measured. (Reference 25).

Power Density (of an electromagnetic wave): Power per unit area normal to the direction of wave propagation.

R: A subscript meaning Receiving. (The R in $\widehat{RH}$ does not mean Receiving.)

r: Ellipticity Ratio of an electromagnetic wave in the far-field (Fraunhofer Region):

$$r = \left[\frac{e_{\widehat{RH}} + e_{\widehat{LH}}}{e_{\widehat{RH}} - e_{\widehat{LH}}}\right] \quad \text{Where} \quad \left[(1 \le |r| \le \infty)\right]$$

Note: For a linearly polarized wave $r = \infty$;
For a right-handed circularly polarized wave $r = +1$;
For a left-handed circularly polarized wave $r = -1$.

The Ellipticity Ratio of an antenna is that of the far-field wave the antenna would radiate in free-space. See Figure D1, where $e_{\widehat{RH}}$ and $e_{\widehat{LH}}$ are twirlors.

r_C: Ellipticity Ratio of a Circularly polarized wave or antenna. See r.

Note: For a right-handed antenna or wave, $r_C = +1$
For a left-handed antenna or wave, $r_C = -1$

r_E: Ellipticity Ratio of an Elliptically polarized wave or antenna. See r.

r_R: Ellipticity Ratio of a Receiving antenna. See r.

r_T: Ellipticity Ratio of a Transmitting antenna. See r.

r_{RC}: Ellipticity Ratio of a Receiving antenna that is Circularly polarized. See r_R and r_C.

Γ_{TC}: Ellipticity Ratio of a Transmitting antenna that is Circularly polarized. See Γ_T and Γ_C.

r_1: DR. LEONARD HATKIN'S symbol for his "Axial Ratio" of the receiving antenna, where $r_1 = |\Gamma_R|$ such that r_1 does not carry a sign to indicate sense. See Γ & r_2.

r_2: DR. LEONARD HATKIN'S symbol for his "Axial Ratio" of the transmitting antenna, where $r_2 = |\Gamma_T|$ such that r_2 does not carry a sign to indicate sense. See Γ & r_1

Racon: Radar Beacon, See IRE Dictionary of Electronics Terms and Symbols (reference 25).

RAS: An acronym for Reply Antenna Selection; coined in this paper.

RESA: Scientific Research Society of America.

$\widehat{RH}$: A subscript meaning Right-Handed. See $\widehat{LH}$ and Sense.

ΣA: The sum of additional power attenuations such as transmission line losses, expressed in + db.

ΣG: The sum of additional power gains such as could be given by a preamplifier at the output port of a receiving antenna, expressed in + db.

Sense, of an electromagnetic wave (or an antenna): The direction of rotation of the electric field voltage vector ϵ (or "twirlor" if circularly polarized). The definition of sense used in this paper is the one given by the IRE (now IEEE): A right-handed (RH), or clockwise, polarized wave is an elliptically polarized (including circularly polarized) transverse electromagnetic wave in which the rotation of the electric field voltage vector ϵ at a point in a fixed plane normal to the direction of propagation of the wave is clockwise for an observer looking in the direction of propagation. This definition of sense is opposite to the one used in classical physics. See Γ.

Sexad: Abbreviation for Sexadecimal, a sixteenth part.

τ (Tau): Tilt Angle. The angle between the major axis of the polarization ellipse of an electromagnetic wave (or antenna) and a line in the θ direction tangent to the sphere of observation. See Figure D1.

θ (Theta): Polar angle; one of two angles used to specify a point on the surface of a sphere of observation. The other angle is Φ. See Figure D1.

T: A subscript used to indicate Transmitting.

"Twirlor": A physically observable constant-magnitude electric vector that rotates in a fixed plane about a fixed point (the field voltage components $\epsilon_{\widehat{LH}}$ and $\epsilon_{\widehat{RH}}$ are twirlors). In the Fraunhofer Region, the electric field of any electromagnetic wave observed at a fixed point in a plane normal to the direction of propagation appears as (or can be resolved into) either:

1. A single twirlor (the wave is circularly polarized).
2. Two twirlors of equal magnitudes but of opposite directions of rotation (the wave is linearly polarized).

3. Two twirlors rotating in opposite directions and of unequal magnitudes (the wave is elliptically polarized).

> Note 1: The Relative Phase Angle δ' between two counter-rotating twirlors determines the Tilt Angle τ of the polarization ellipse of the wave (including the case of linear polarization, in which the ellipse is a straight line).
>
> Note 2: Any receiving antenna that captures energy from a radio wave responds to the observable field voltage vector ϵ (which may or may not rotate and, if it does, may or may not vary in magnitude during a revolution) by delivering across two terminals of its output port an alternating potential difference that varies sinusoidally at the frequency of the radio wave. This potential difference can be expressed in terms of its peak value, or in terms of its RMS value (which is the method used in this paper).
>
> Note 3: A term coined in this paper. See R. W. P. KING, H. R. MIMNO AND A. H. WING (reference 34), page 175.

URSI: Union Radioscientifique Internationale (International Scientific Radio Union). See CCIR (URSI is a participant) and reference 65.

USAF: The United States Air Force.

USN: The United States Navy.

V : Velocity of a radio wave (or a light wave) in a non-bounded vacuum (free-space). The URSI value is:

$$V = (299,792_{\blacktriangle}5^{\blacksquare} \pm 0_{\blacktriangle}4^{\blacksquare}) \text{ km/Sec.}, = (299,792,5^{\blacktriangledown}00^{\blacksquare}_{\blacktriangle} \pm 4^{\blacktriangledown}00^{\blacksquare}_{\blacktriangle}) \text{ m/sec.}$$

W : Reference Power Level, ordinarily one watt.

X : Polarization Mismatch Loss (PML) expressed in + db. See Equation 1, where the value of X is to be inserted, and Equations 2 thru 7 for calculating the value of X.

Yard, International: 1■ International Yard = 0▲9144■ Meter. (reference 42).

2KFT▲AQSP: A descriptive numbering system for antenna radiation patterns. See Figures D2A and D2B.

▼: Alcedo (q.v.)

■: Pega (q.v.)

▲: Picus (q.v.)

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* 46. All documents are unclassified.

* 47. Author's name is indicated thusly: A.U. THOR.

* 48. Anonymous publications are treated as though authored by the issuing organization.

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Six of the major references used in the preparation of this paper contain the following relevant typographical errors:

a. LEONARD HATKIN, Senior Research Scientist, U.S. Army Signal Research & Development Laboratories, Belmar, N.J. has informed the writer that Equation (1) of "Elliptically Polarized Waves", by LEONARD HATKIN (reference 22) does incorrectly quote Equation (2) of "Antenna for Circular Polarization" by W. SICHAK and S. MILAZZO (reference 55) by misprinting of the term:

$$\mp\left[\frac{2r_2}{(r_2^2+1)} \quad \frac{2r_1}{(r_1^2+1)}\right] \quad \text{as:} \quad \mp\left[\frac{2r_2 \quad r_1}{(r_2^2+1)\ (r_1^2+1)}\right].$$

b. M.L. KALES, Mathematician, Electronics Division, Naval Research Laboratory, Washington D.C., has advised the writer that Equation (46) of "Techniques for Handling Elliptically Polarized Waves with Special Reference to Antennas", by V.H. RUMSEY, G.A. DESCHAMPS, M.L. KALES and J.I. BOHNERT (reference 51) does have a term:

$(4r_i \quad r_t^2)$ that is a misprint of: $(4r_i \quad r_t)$.

M. L. Kales volunteered the information that the same equation has the factor $2(1+r_i^2)(1-r_t^2)$ in the numerator whereas it should be in the denominator, as can be seen by referring to Equation (43), which, according to M. L. Kales, is believed to be correct.

c. In Appendix D hereto, reference is made to Figure 15-1, on page 444, of Antennas by JOHN D. KRAUS (reference 38). This figure has $\theta = 0^\circ$ in a place where it should read $\theta = 90^\circ$.

d. The IRE Dictionary of Terms (reference 25), in the definition of Fraunhofer Region includes a note in which the phrase "Fresnel region" should be "Fraunhofer region".

e. The IRIG Standard Coordinate System and Data Format for Antenna Patterns (reference 29), of which the writer was one of ten authors, contains typographical and omission errors, as follows:

On Page 35: Fails to mention that in the Linear Component Method, one must observe also the "sense" of the wave.

On Page 8: "Tilt Angle" is omitted from the list of definitions. However, Tilt Angle is defined at the bottom of Page 38.

On Page 25: The first item of the Bibliography should be ASA Standard No. C16.11 instead of C76.77.

NOTE: It is the intention of the ETMWG, the Electronic Trajectory Measurements Working Group of IRIG, of which this writer was the 1962 & 1963 Chairman, to prepare and have issued in the near future an improved and expanded edition of the IRIG Standard. Meanwhile, a second printing dated April, 1963, has added (on page 35), a requirement to observe the "sense" (and has elsewhere several corrections of minor typographical errors). The forthcoming revised edition will include magnetic tape and punched tape formats for antenna radiation pattern data. Readers are requested to advise the IRIG Secretariat of any errors found in the Standard, and to suggest improvements for future editions.

f. Antenna Polarization Analysis By Amplitude Measurement of Multiple Components by L. CLAYTON and J.S. HOLLIS (reference 10) has a typographical error in the last line of page 20. E_4^4 should be E_4^2 (as can be seen by the same equation on page 22). [This error was corrected in a later publication of this article (see Reference 10).]

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INDEX*

*NOTES:

Greek letters are given first.

Personal names are given thusly: A. U. THOR (or THOR, A. U.).

Star (★) indicates cited author.

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* The Rice University (Houston, Texas), formerly called the Rice Institute (founded by WILLIAM MARSH RICE).

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REMOVABLE COPIES OF PAGES 4 AND 5.

For the convenience of the reader, removable copies of the two pages that have the Power Transfer Equation (Equation 1) and the Polarization Mismatch Loss Equations (Equation 2 through Equation 7) are included as not-numbered sheets following the next page. These removable (perforated) sheets are printed on translucent paper so they can be easily reproduced.

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$$P_{R(dbW)} = P_{T(dbW)} + \left[G_{T(dbI)} + G_{R(dbI)} + \Sigma G_{(db)}\right] - \left[X_{(db)} + \Sigma A_{(db)}\right] - \left[20 \log_{10} D_{(L)} + K + 20 \log_{10} F_{(Mc/S)}\right] \quad (1)$$

<u>Where:</u>

P_R = Power available at output port of receiving antenna (in $\pm$ db with respect to reference power W, ordinarily one watt).

P_T = Power into input port of transmitting antenna (in $\pm$ db with respect to reference power W).

G_T = Transmitting antenna's power gain in direction of receiving antenna (in $\pm$ db relative to isotropic antenna having no loss).

G_R = Receiving antenna's power gain in direction of transmitting antenna (in $\pm$ db relative to isotropic antenna having no loss).

ΣG = Sum of any additional power gains (in+ db).

X = Polarization mismatch loss (in+db). (<u>See equations on next page</u>)

ΣA = Sum of any additional power attenuations (in+db).

D = Distance between the two antennas (in L units).

K = Constant depending on L, the unit of length selected; where ▲ (picus) is a decimal point:

L	K	L	K
Foot, International . .	-37▲87	Kilometer	+ 32▲45
Yard, International . .	-28▲33	Mile, Statute . .	+ 36▲58
Meter	-27▲55	Naut. Mi., Int. .	+ 37▲82

F = Frequency, in Megacycles per Second, or in Mega Hertz (MHz).

QUALIFYING NOTES FOR THE POWER TRANSFER EQUATION:

a. In Equation 1, it is assumed that there is only one signal source and no noise sources.

b. Equation 1 is valid only when each of the two antennas is in the far-field or Fraunhofer Region of the other, here defined as beginning at a distance of $2d^2/\lambda$ and extending infinitely, where d is the largest projected linear dimension of the antenna aperture and where λ is the wavelength (references 26, 56 and 64).

c. For antennas in other than a non-bounded vacuum, Equation 1 would be slightly in error in that the values given for K were calculated for the vacuum velocity of propagation, V (reference 65). For most real cases, this error is extremely small and can be ignored.

d. For antennas in other than a non-bounded vacuum, one must allow for the effects of the medium and its boundaries. See Appendixes A through E.

e. For definitions of symbols and terms, see Appendix E.

NOTE: *Equations (1) thru (7) are from Air Force Western Test Range Technical Report AFWTR-TR-65-1, by* BEUHRING W. PIKE, P. E.

Case: (Polarizations)	X = Polarization Mismatch Loss (in+db) =	
Ellip. ⟷ Ellip.	$-10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{4\Gamma_T \Gamma_R + (1-\Gamma_T^2)(1-\Gamma_R^2)\ (\mathrm{Cos}\ 2\beta)}{(1+\Gamma_T^2)\ (1+\Gamma_R^2)} \right] \right\}$	(2)
Ellip. ⟷ Lin.	$-10 \log_{10} \left\{ \frac{1}{2} - \frac{1}{2} \left[\frac{(1-\Gamma_E^2)\ (\mathrm{Cos}\ 2\beta)}{(1+\Gamma_E^2)} \right] \right\}$	(3)
Ellip. ⟷ Circ.	$-10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{2\Gamma_C \Gamma_E}{(1+\Gamma_E^2)} \right] \right\}$	(4)
Lin. ⟷ Lin.	$-10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\frac{(\mathrm{Cos}\ 2\beta)}{1} \right] \right\}$	(5)
Lin. ⟷ Circ.	$-10 \log_{10} \left\{ \frac{1}{2} - \frac{1}{2} \left[\frac{0}{2} \right] \right\} = +\ 3\ \mathrm{db}$	(6)
Circ. ⟷ Circ.	$-10 \log_{10} \left\{ \frac{1}{2} + \frac{1}{2} \left[\Gamma_{TC}\, \Gamma_{RC} \right] \right\}$ = 0db When $\Gamma_{TC} = \Gamma_{RC}$ $= +\infty$ db When $\Gamma_{TC} = -\Gamma_{RC}$	(7)

Where*4: Γ = Ellipticity Ratio, the signed voltage ratio of the major axis of the polarization ellipse to its minor axis, where $(1 \leq |\Gamma| \leq \infty)$. *5

β = Polarization Mismatch Angle, $(0^\circ \leq \beta \leq 90^\circ)$. *5

T means Transmitting; R means Receiving.

E means Elliptically Polarized; C means Circularly Polarized.

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*4: For definitions see Appendix E, Glossary of Symbols and Terms.

*5: See Appendixes A through E.

NOTE: Equations (1) thru (7) are from Air Force Western Test Range Techn. Report AFWTR-TR-65-1, by BEUHRING W. PIKE, P. E.

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13. ABSTRACT

The literature abounds with examples of a convenient equation ("the beacon equation") for calculating the free-space power transfer between two widely spaced radio antennas having polarizations that are matched for maximum power transfer. On the other hand, convenient equations for making such calculations where the polarizations are not matched are very scarce. In this paper the well known beacon equation has been combined with a published (but relatively little known) general equation for polarization mismatch loss, so as to yield a complete general equation for calculating the power transfer between two widely spaced antennas in free-space. For convenience, the portion of the general power transfer equation that accounts for polarization mismatch loss has been reduced to yield a special equation for each of the five limiting cases. Also given are discussions of polarization problems and solutions in radio and radar and a discussion of antenna radiation field representation methods and their use in calculating the power transfer between two antennas. This 75 page Technical Report includes a Glossary of terms and a Bibliography of 68 references.

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